Environmental Controls on Installed Woody Plant Establishment in the Hydrologically Restored Tidal Freshwater Wetlands of the Nisqually River Delta

Caitlin Rose Guthrie

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Committee:

Kern Ewing

Jonathan Bakker

Jesse Barham

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University of Washington

Abstract

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Caitlin Rose Guthrie

Chair of the Supervisory Committee:
Professor Kern Ewing
School of Environmental and Forest Sciences

Tidal freshwater wetlands are some of the most highly productive wetland systems on the planet. However, alterations to the land surrounding major Puget Sound river deltas have resulted in a 60% to 83% loss of tidal wetlands. As our awareness of ecological services grows, and freshwater tidal wetlands rise in restoration priority, understanding the environmental controls on this native habitat type is of the utmost importance. Currently, a lack of scientific knowledge leaves data gaps for tidal swamp restoration implementation. The purpose of this study was to determine the relationship between restored tidal processes and installed native woody plant establishment in a Puget Sound tidal swamp. In this observational study, we determined survivorship, growth and vigor of installed plants, while also measuring numerous environmental controls, including: elevation, water table depth, competition, salinity, and soil characteristics (moisture, pH, texture, bulk density and organic matter). Planting success was significantly correlated with elevation, depth to water table, salinity, soil organic matter, and soil bulk density. Increased planting success occurred at higher elevations, deeper water tables and lower salinities. At growing season salinities above three ppt and at elevations below ½ meter above mean higher high water, planting success was greatly reduced. However, specific installed species, including *Malus fusca*, *Lonicera involucrata* and *Rosa pisocarpa* survived at higher rates in these marginal conditions. By gaining an understanding of processes and natural patterns, we are able to advance the efficacy of future Pacific Northwest tidal forested restoration projects.

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Glossary

Ecological Restoration – "Intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity, and sustainability" (SER, 2004).

Ecosystem services – The quantifiable services that an ecosystem provides to humans, including provisioning services (such as salmon, fiber and timber), regulating services (such as water quality and flood prevention) and supporting services (such as nutrient cycling and plant pollination) (Dodds, et al, 2008).

Estuary – A semi-enclosed coastal body of water that has open connectivity with the sea.

Habitat – The physical and biological environment that surrounds, influences and is utilized by a species population.

Mean higher high water – the mean elevation of the two high tides of the day, averaged over a 19-year period (NOAA, 2012).

Mean lower low water – the mean elevation of the two low tides of the day, averaged over a 19-year period (NOAA, 2012).

Nisqually River Estuary – The mouth of the Nisqually River, where river currents meet coastal tides, extending up the river to the Mounts Road Bridge (at least).

Oligohaline – Brackish water with a salinity of 0.5 to 5.0 parts per thousand from ocean-derived salts.

Pulsed flooding cycles – Flooding that occurs on a regular measurable pattern, in this case, as a result of ebbing and flowing oceanic tides.

Reference site – A site with geographic proximity, ecological similarity and hydrologic similarity to the restoration site. A reference site also has plant associations and species richness representative of the endpoint of the restored site's trajectory.

Restoration site – A site that is returning from an impaired ecological state to a stable and sustainable site with increased ecosystem services. In this paper, restoration site refers more specifically to areas at which historical tidal processes have been returned in the Nisqually River Estuary.

Restoration Success – The creation of physical and biological conditions that allow an ecological system to provide increased ecosystem services and to meet defined goals.

Saline soils – Soils containing 2 parts per thousand soluble salts in the saturation extract.

Tidal freshwater swamp – A low-lying wetland with hydric soils adjacent to the upper reach of an estuary, that is dominated by trees, is periodically inundated by low salinity water (<0.5 ppt) and is tidally influenced by tidal exchange and river flow (Mitsch & Gosselink, 2007).

Tidal dike – The constructed embankment of earth and/or rock built to prevent tidal waters from entering the floodplain.

Tidal reconnection – The removal of human-made embankments, allowing tidal waters to flood and repossess the floodplain.

Introduction

Wetlands Overview

In recent history, wetland extent in the United States has followed a path of decline, as documented by the Environmental Protection Agency from the 1950s to present (Dahl, 2011). While the rate of wetland loss has slowed overall from the 1970's to the present, the years 2004 – 2009 saw an annual decrease of 13,800 acres annually (Dahl, 2011). However, in the past few decades, the substantial value of ecosystem services provided by wetlands has been increasingly acknowledged and quantified (Dodds, et al., 2008). Also, wetland ecological function can be restored to a greater degree, in less time, as compared to other ecosystem types (Dodds, et al., 2008). The knowledge of ecosystem function value, joined with the relative ease of restoration, has led to substantial wetland restoration efforts in the United States (Dodds, et al., 2008), including in tidal systems (Conner, et al., 2007).

The majority of restoration work occurring in tidally influenced areas of the Pacific Northwest takes place in estuarine wetlands (as opposed to marine wetlands) (Dethier, 1990). Estuarine wetlands include mangrove forests, freshwater swamps, salt marshes, brackish marshes, intertidal mudflats, and open water wetlands (bays, sounds and coastal rivers). Marshes can be further divided into high marshes, located above the elevation of mean higher high water (MHHW) and low marshes, located below the elevation of MHHW (Mitsch & Gosselink, 2007). Estuaries and estuarine wetlands are differentiated from the open sea in that the salt water within estuaries is diluted with freshwater from rivers and streams draining the adjacent land (Pritchard, 1967).

Estuaries are also generally locations of enhanced economic opportunity, leading to concentrated human development, such as ports, cities and industrial centers. Living in coastal areas is so valued, that as of 2008, 159,754,000 people, or 52% of the U.S. population lived in a coastal county (Crossett, et al., 2004). Between 1980 and 2008, there was a net growth of 1.7 million people, a 54% population increase, in coastal areas of Washington State (Crossett, et al., 2004).

In the Puget Sound, losses of tidal wetlands (including both freshwater and saline) occurred during the late 1800's and early 1900's, as European settlers diked, ditched and filled wetlands associated with major river deltas. The diking of tidal wetlands breaks the lateral connection between wetlands, the river channel, the estuary, and the frequently flooded adjacent uplands. Total losses of Puget Sound tidal wetlands are estimated to be between 60% and 83%, including wetlands created since the historical reference (Collins & Sheikh, 2005 and Tanner, et al., 2002). When tidal wetlands are lost, the corresponding wetland functions are lost as well and ecological processes are interrupted (Garono, et al., 2006). In the Puget Sound, fish and wildlife populations that depend on estuaries, including several federally listed threatened salmon species, have declined dramatically as a result of wetland loss (Dean, et al., 2000). Numerous plans identify tidal wetland restoration as crucial for regaining lost ecosystem functions (Puget Sound Water Quality Authority, 1991; Puget Sound Partnership, 2008; and Nisqually River Council, 2010).

Tidal Freshwater Wetlands

Historically, tidal freshwater wetlands were found in many estuarine systems. Tidal freshwater wetlands provide key ecosystem services by protecting coastal lands from storm surges and coastal erosion, filtering out sediments, and sequestering nutrients (Zedler & Callaway, 2001 and Maurizi & Poillon, 1992). Tidal wetlands also provide habitat for coastal organisms and are valued by people for recreation, timber production, food production, archeological values, and aesthetics (Maurizi & Poillon, 1992).

Tidal freshwater wetlands form on lands with low topographic relief adjacent to coastal rivers (Courtwright & Findlay, 2011). These wetlands are defined as having a soil pore water average salinity of less than 0.5 parts per thousand (ppt) due to freshwater inputs from the river, with higher salinities (up to 20 ppt) potentially found in surface water of nearby tidal channels (Brophy, 2009). The wetlands are hydrologically influenced by tides, with a pulsed flooding cycle (Courtwright & Findlay, 2011). Tidal freshwater wetlands are some of the most highly productive wetland systems on the planet, receiving the benefits of a high energy system and influx of nutrients without the stress of high salinity found in saltwater tidal systems (Mitsch & Gosselink, 2007 and Begon, Harper, & Townsend, 1986). However, the positioning of tidal freshwater wetlands at the confluence of rivers and oceans leaves them vulnerable to salt water intrusion, stormwater runoff and climate change (Doyle, et al., 2007) and very desirable for human development.

Tidal freshwater wetlands in general, and tidal freshwater forested wetlands (also known as tidal freshwater swamps) in particular, are also some of the least studied ecosystem types in the United States (Conner, et al., 2007). This lack of scientific knowledge leaves data gaps for those who lead the implementation of restoration projects. As our knowledge of ecological services grows, and freshwater tidal wetlands rise in priority, an increase in future restoration is likely. In order to successfully execute these projects, and to restore ecosystem function, we must develop a thorough understanding of the environmental processes governing the creation of tidal freshwater wetlands (Table 1).

Tidal swamps are described as wetlands dominated by woody vegetation, including both trees and shrubs. Internationally, in undisturbed conditions, tidal swamps are found high in the estuary, in the tidal freshwater zone, the oligohaline zone (salinities of 0.5 – 5.0 ppt) and the mesohaline zone (salinities of 5.0 – 18.0 ppt). Additionally, tidal swamps can be found on the margin of the marine zone, such as along freshwater tributaries, where freshwater is diluting saline ocean water.

Research on tidal swamps has focused on the mangrove-dominated habitats of the southeastern U.S. Mangroves are facultative halophytes and are generally found in tidal saline systems. The hydrologic flooding patterns in these ecosystems are dynamic, due to the interaction between tides, river flows, groundwater levels and saltwater surges (Day, et al., 2007). This dynamic inundation regime results in complex biogeochemistry (Anderson & Lockaby, 2007) that directly influences plant community composition (Day, et al., 2007).

Controlling Factors →	**Habitat Structure** →	**Habitat Processes** →	**Ecosystem Functions**
Substrate	Density	Production	Prey Production
Currents	Biomass	Sediment Flux	Flood Protection
Sediment Supply	Microtopography	Nutrient Flux	Refuge
Hydrology	Diversity	Carbon Flux	Carbon Sequestration
Slope & Depth	Patch Size		Nutrient Transformation
Pollution & Nutrients	Landscape position		Biodiversity Maintenance
Light (shading)			Diversity Regulation
Other disturbances			

Table 1: Conceptual model showing the organization and interaction of ecosystem components to consider in the evaluation of tidal freshwater wetland restoration potential (adapted from Thom, 2005).

Ecological processes in Pacific Northwest tidal freshwater swamps are similarly complex and are not well understood, due to minimal research. These increasingly rare and threatened ecosystems form where terrestrial and estuarine habitats overlap and hydrogeomorphic processes are dynamic. Tidal wetlands provide habitat for a high diversity of species (Bunn & Arthington, 2002). Specifically, research indicates that tidal wetlands produce a large quantity of prey for young out-migrating salmon (Garono, et al., 2006) and that juvenile salmon extensively use tidal freshwater floodplain habitat to grow and feed during their out-migration (Bottom, et al., 2005 and Bottom, et al., 2008). In general, a wide variety of aquatic animals are sustained by the connectivity between rivers and floodplains in the tidal zone (Bunn & Arthington, 2002). One current theory is that the higher the structural diversity found within a tidal wetland, the more biomass processing and invertebrate production that occurs (Garono, et al., 2006). To restore these functions of tidal freshwater forests, we must understand both how the forests affect and are impacted by the hydrogeology of the environment (Hood, 2007).

Once a tidal wetland is separated from its natural hydrology via diking and ditching, it becomes increasingly difficult to restore ecological structural diversity. After tidal wetlands are diked, subsidence is common due to oxidation of soil organic matter following artificial drainage, lack of tide-borne sediment deposition, and compaction due to grazing and farm equipment (Frenkel & Morlan, 1991 and Cornu & Sadro, 2002). As tidal wetlands are altered by farming practices, and become drier post diking, the soils, elevations, topography and plant communities are consequently modified as well.

Additionally, controlling factors often exist that limit tidal forest restoration potential for both process and structure (Palmer, et al., 2005). For example, dams and other hydrologic modifications upstream alter the sediment budget and hydrology of the tidal floodplain ecosystems (Wolanski, et al., 2004). Sediment becomes trapped behind dams, decreasing both outflow and the potential for accretion in a river's lower reaches and estuary. Another controlling factor that could limit restoration success is historical land use, such as conversion to agriculture. Post-agricultural environmental conditions have been shown in other Pacific Northwest ecosystems to exercise long lasting control on plant community successional patterns within restoration sites (Bakker & Berendse, 1999).

Restoration efforts in large coastal rivers and estuaries have focused on recreating hydrologic connections between the floodplain and main stem rivers, and between oceans and historic tidal channels (Simenstad & Warren, 2002). When historic tidal sloughs and back- waters are newly re-exposed to tidal forcing, dynamic changes to vegetative communities and channel morphology follow (Coats, et al., 1995 and Zedler & Callaway, 2001). The research cited above and following indicates that the recreation of hydrologic connection is often only the first step needed to accelerate the recovery of tidal forest ecosystems.

When tidal dikes are removed or breached to hydrologically restore a site, the historical ecosystem does not generally immediately follow. Tidal wetlands are extremely elevation sensitive, with small changes in elevation resulting in drastic changes in vegetative composition and succession, geomorphological evolution, and fish habitat use (Zedler, et al., 1999 and Rice, et al., 2005). It takes years-to-decades for sediment and organic matter to accumulate, counteracting the effects of subsidence and partially recreating the necessary conditions for ecosystem restoration. At one previously diked and subsided tidal site in Oregon, it was estimated that the reestablishment of tidal marsh would require over 50 years of sediment accretion (Frenkel & Morlan, 1991).

Many vegetated tidal zones consist of marshes that lack woody plant communities (Jefferson, 1975) and it is theorized that tidal swamps will take even longer to naturally reestablish than tidal marshes, due to the slower growing woody vegetation and higher elevations requirements of tidal swamps (Brophy, 2009). Limited scientific evidence delineates the conditions under which specific shoreline-adapted woody plants may establish, or survive (if planted into habitat restoration projects).

In recent years, there has been extensive study of the Columbia River Estuary's existing tidal freshwater Sitka spruce (*Picea sitchensis*) dominated swamps (Diefenderfer, et al., 2008). Diefenderfer et al. found 70 cm land surface subsidence in a formerly diked tidal swamp in Washington (2008). After dike removal, the hydrologically restored land gained soil at a depth of 2.4 cm/year accretion. From these measurements, they estimate that it will take 20 to 54 years or more for the land to recover to historical elevations (Diefenderfer, et al., 2008). It is feasible that under different conditions, the hydrologically restored land could accrete rapidly. In that case, the influx of sediment would alter soil organic matter content and bulk density, resulting in changed conditions for establishing plants. Just as it has been demonstrated that environmental conditions affect plant composition, plant community composition affects the environmental conditions of a site.

Specifically, the vegetative composition within a tidal freshwater wetland directly affects many of the physical, chemical and biological elements and relationships of the system. Light availability, rates of sediment deposition/erosion, prey production, carbon flux and nutrient flux are all altered by the vegetative composition (Garono, et al., 2006). In hydrologically restored tidal wetlands, a positive feedback loop has been demonstrated after the reestablishment of native vegetation. The accumulation of organic matter and sediment increases as rates of decomposition slow due to increased anoxic conditions, and as the plant matter physically catches and holds sediment (Turner, et al., 2000). The increased roughness of vegetated areas also slows the velocity of water, which allows fine sediments to settle out (Turner, et al., 2000).

Tidal wetland plants have been shown to alter microclimate and raise elevation to the extent that they aided succession to a wholly new plant community. For example, researchers in the Pacific Northwest have observed evidence of a successional series from a tidal rush wetland, to a wet shrub community, to a climax pine/spruce forested swamp community (Franklin & Dyrness, 1988). The amount of time it takes a system to naturally progress through these successional stages depends on many factors, including the landscape setting and the disturbance regime. This research demonstrates that understanding how tidal wetland communities change over time, and in response to disturbance, is essential in the development of successful restoration plans.

It is often the goal of restoration practitioners to accelerate the processes of succession, generally by modifying the site to support later successional species. In tidal wetland communities, the low surface elevation of the land can slow or prevent succession (Zedler, et al., 1999). Cornu and Sadro studied the possibility of taking an active restoration approach to accelerate succession within a tidal wetland by manipulating the surface elevations (2002) (documentations of other active tidal wetland elevation restoration modifications are found in Coats (1995) and Williams & Faber (2001)). In this type of highly dynamic system, it is unclear as to whether installed fill will remain stationary or be redistributed offsite, how much compaction and subsidence will occur after the placement of fill, and whether the functional elevation will perform as predicted. Their initial results indicated that it is possible to influence tidal wetland hydrology and ecosystem response through the manipulation of surface elevation to speed ecological succession (Cornu & Sadro, 2002). However, depending on the size of the site and whether a source of sediment is available, this method may not be cost effective.

Recent scientific study of undisturbed tidal wetland habitat has demonstrated the potential importance of microtopographic variation on succession within tidal wetlands. Undisturbed tidal wetlands exhibit diverse microtopography, and the ecological functions of tidal wetlands are interconnected with the microtopography (Garono, et al., 2006). Microtopography has been used as a restoration performance measure due to the resulting variability in hydrologic inundation levels throughout a site. The interaction between water level and land elevation leads to a multitude of microhabitats and an increase in both tidal plant species richness and diversity (Moser, et al., 2007 and Wolanski, et al., 2004).

The microtopography that is found in temperate tidal forested wetlands is often caused by large, slowly decomposing wood underneath hummocks. In the Pacific Northwest, this has been observed in undisturbed Sitka spruce swamps (Kunze, 1994). However, in historically diked and farmed tidal swamps, all large woody debris and stumps were removed as a matter of course. These past actions result in a lack of topographic relief in hydrologically restored tidal wetlands (Martin, 1997). Multiple studies have indicated that the presence of large woody debris in tidal wetlands and riparian floodplains has a strong controlling factor on plant distribution, community composition and succession (Fonda, 1974; Maser & Sedell, 1994; and Hood, 2007).

Plants that establish on top of hummocks are exposed to less frequent, less intense flooding than plants that establish in hollows, or on land lacking topographic variation. Microtopography within a tidal wetland allows for the establishment of trees and shrubs that cannot tolerate high levels of tidal flooding (Diefenderfer, et al., 2008). Woody plants respond to the complex, interrelated environmental stresses of flooding in a variety of ways that result in decreased vigor and often death. Seedlings that are installed in restoration plantings are at an increased risk of flooding related mortality as compared to established trees (Glenz, et al., 2006).

Another factor affecting plant establishment and growth is salinity. Elevated salinity results in decreased photosynthesis in upland plant species (Longstreth & Nobel, 1979). Nutrient deficiency (Lovett & Tobiessen, 1993) and low redox levels (Ewing, et al., 1991) are other factors that can co-vary with salinity, and result in lower levels of photosynthesis. Decreased photosynthesis and other negative physiological salinity related effects, such as reductions in both productivity and in leaf expansion, can lead to death in newly installed seedlings (Smit, et al., 1990 and Smit, et al., 1989). Additionally, flooding tolerances vary in between species, even those that are closely related (Kozlowski, 2000). Once a plant has established, elevated salinity results in a slower growing, stunted plant (Bernstein, 1975).

Some woody species have higher tolerances for salinity than others (Appleton, et al., 2003 and WSU Native Plant Salvage Project, 2007), but none of the Washington State native woody plants, with the exception of sweet gale (*Myrica gale*), are known to be adapted to live in saline soils (defined as containing more than 2 ppt sustained salinity) (Island County, 2005). However, it is possible that genotypes of a given species found near the coast may be better adapted to increased levels of salinity. Brophy describes tidal swamps in Oregon with salinities in the mesohaline range (5 – 20 ppt) that are dominated by a Sitka spruce canopy with a black twinberry (*Lonicera involucrata*) shrub layer and other tidal swamps with salinities in the oligohaline range (<5 ppt) that are dominated by Hooker's willow (*Salix hookeriana*) (2009).

In the case of tidal freshwater swamps, there are many benefits to actively planting native vegetation instead of passively preparing the site for succession. Restoration plantings can decrease erosion, increase cover and shade, and reduce invasive species, such as reed canarygrass (*Phalaris arundinacea*). Research on similar systems and lab studies on the response of plants to specific stressors can yield implications for restoration actions. In addition, promising research has recently been published on the morphology, ecology and restoration of tidal freshwater swamps (Diefenderfer, et al., 2008; Brophy, 2009; Franklin & Dyrness, 1988; and Kunze, 1994). However, at this point in time, appropriate restoration project reference sites are often lacking. Additional investigation into the ecology of tidal swamps is sorely needed for practitioners to choose, design and evaluate the success of tidal swamp restoration (Brophy, 2009).

Study Site

The Nisqually River Delta is located in Washington State, in Thurston and Pierce counties, 16 km NE of Olympia, Washington (Figure 1). It formed at the confluence of the Nisqually River and McAllister Creek, where they enter the south Salish Sea, Puget Sound. The study area was confined to potential tidal forested wetland habitat that is strongly influenced by freshwater and adjacent to both banks of the Nisqually River as it enters the delta (study area expected to be freshwater based on elevation, proximity to freshwater channels and observations of restoration practitioners (Barham & Sampselle, pers. comm.).

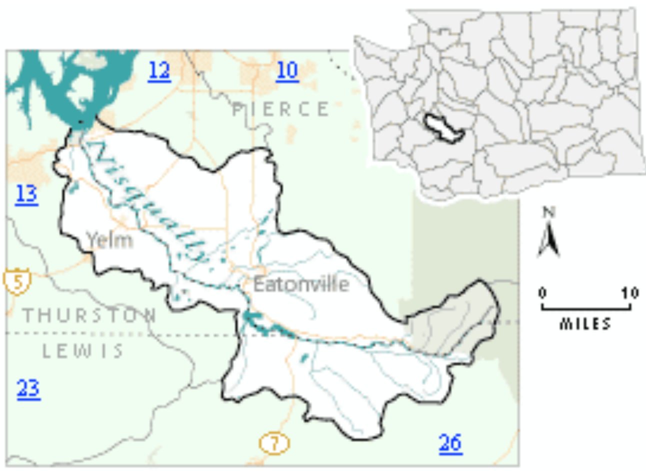

Figure 1: Nisqually watershed (Washington State Department of Ecology, 2010).

History

The Nisqually River delta has been known and used by the Nisqually Indian Tribe since before historical record. In 1854, the Treaty of Medicine Creek was signed at what is now known as McAllister Creek, within the current boundaries of the Nisqually National Wildlife Refuge (NNWR). Among other actions, the treaty recognized native fishing and hunting rights (Meany, 1909). Starting in the late 1800's, white settlers started to convert the arable floodplains and tidelands of the Puget Sound region into agricultural lands and pasture. Alson L. Brown purchased a large portion of the Nisqually delta in 1904 and he installed substantial dikes and ditches, creating the Brown Farm. In addition to farming activities, logging occurred on site, as determined from physical evidence (pilings and cables), which remained in the tidal freshwater wetlands until at least the 1980s (Kunze, 1984). It was common practice in this era for white farmers to remove all stumps and logs from diked agricultural lands (Martin, 1997). These practices were most likely followed on portions of the Brown farm as evidenced by the low topographic relief that can be presently observed (recall that microtopography in tidal wetlands and floodplains is formed by slowly decaying large woody debris (Kunze, 1994)). Other portions of the farm originally consisted of salt marsh, and lacked woody vegetation.

The Treaty of Medicine Creek had not been upheld in the decades since signing and in 1974, the Boldt Decision granted the Nisqually Indian Tribe recognized rights to half of the fish caught within "usual and accustomed" areas (Cohen, 1986). However, a great deal of the Nisqually Indian Tribe's historic fishing areas had been subjected to substantial human-induced disturbance in the previous century. In fact, areas on both sides of the Nisqually River, totaling about 1,000 acres, were still diked in 1974, preventing historical hydrogeomorphic processes and resulting in decreased habitat for out-migrating smolt (NNWR, 2005). Salmon numbers on the Nisqually River were on a path of decline (NNWR, 2005). Also in 1974, the U.S. Fish and Wildlife Service purchased the Brown Farm (Kunze, 1984). Since then, the west side of the Nisqually River estuary and portions of the east side of the estuary have been managed by the U.S. Fish and Wildlife Service (USFWS) as a National Wildlife Refuge. Additional land on the east side of the estuary is owned and managed by the Nisqually Indian Tribe (Barham, pers. comm). A cooperative agreement between the Tribe and the NNWR allows the tribally owned Nisqually River floodplain land to be managed as part of the NNWR.

Disturbances

The Nisqually River Estuary is, and has been historically, affected by physical and biological disturbances. Natural disturbances include flooding, earthquakes (and resulting subsidence), fire and lahars from Mt. Rainer in the upper watershed. Lahars are mud/debris flows originating from the slopes of a volcano that typically flow along a river valley. Lahar flows from the slopes of Mt. Rainer were a significant historical source of sediment in the Nisqually River Estuary (Pringle and Scott, 2001).

Historical physical alterations to the tidal wetlands include filling, diking, and ditching. Biological alterations include farming, grazing, the introduction of nonnative species and the disruption of natural populations. Whereas moderate levels of disturbance can result in increased ecosystem function and help to create a variety of habitats supporting a diversity of native species (Townsend et al., 1997), it is been demonstrated that agricultural activity in previously forested tidal wetlands can result in more homogenous topography at a lower elevation, a lower number of tidal pools, and a deficiency of accumulation of large woody debris- both in tidal channels and on the floodplain itself (Diefenderfer & Montgomery, 2009). Qualitative observations of the Nisqually River estuary confirm these trends.

Knowledge of the extent of disturbances within an ecosystem and in the greater watershed is important for the successful design of a restoration plan. Restoration projects have a greater chance of success if enacted in areas that are largely undisturbed, whereas restoration projects are more likely to fail in areas of high disturbance with a heavily modified surrounding landscape (Garono, et al., 2006).

Restoration

The majority of the Nisqually Delta estuary and associated wetlands are currently owned and managed by the Nisqually Indian Tribe, the WA Department of Fish and Wildlife and the NNWR, as part of the U.S. Fish and Wildlife Service (USFWS). The Tribe owns land on the east side of the river along Red Salmon Slough, while the USFWS owns land on both sides of the river. The NNWR covers 2,925 acres in Thurston and Pierce Counties and contains one of the few remaining large and undeveloped Puget Sound estuaries. The estuary provides important migration and rearing habitat for salmon species, including the fall Chinook salmon, which is listed as federally threatened (USFWS, 2005).

In 1996, the Tribe removed dikes from historical pasture land (the Braget property) on the east side of the Nisqually River, in a pilot study that inundated nine acres of wetlands. The project was mitigation for wetland impacts due to the construction of the Clear Creek Hatchery, as well as a pilot project for restoring tidal habitat for endangered Puget Sound salmon and other wildlife populations. In 2002, building on the success and knowledge gained by the pilot study, the Tribe removed dikes to re-connect tidal influence to 31 more acres (Figure 2). An additional 100 acres of salt marsh and tidal freshwater wetlands on the Braget property were restored via dike removal in 2006 along with 50 additional acres of floodplain and riparian woody plantings (Ellings, et al., 2010).

Figure 2: Nisqually National Wildlife Refuge and Nisqually Indian Tribe estuary restoration projects initiated from 1996-2009. Red lines follow impacted areas (map from Nisqually Indian Tribe, 2009).

The NNWR decided to follow suit after completing a Comprehensive Conservation Plan/Environmental Impact Statement (EIS) analysis, in accordance with the National Wildlife Refuge System Improvement Act and the National Environmental Policy Act (NNWR, 2005). A final decision was reached after considering a range of alternatives, input from the public, stake-holder comments, an analysis of bird habitat preferences, a regional analysis of wetland types (saline versus freshwater wetlands), an analysis of fish habitat benefits and modeling of site hydrology and sediment transport (NNWR, 2005). One of the conclusions reached was that the habitat contained within the NNWR was no longer benefiting migratory waterfowl and other birds, as originally intended. Dominance of invasive reedcanary grass, succession to shrub habitat, a limited ability to manage water levels and deterioration of the dikes all contributed to the EIS recommendation to breach the dikes (USFWS, 2005).

In 2009, the NNWR partnered with Ducks Unlimited to remove the Brown Farm Dike, re-establishing tidal processes to 762 acres of salt marsh and tidal freshwater wetlands. Combined with previous efforts by the NNWR, the Tribe and other partners, the removal of these dikes represented the largest estuary restoration in Puget Sound to date (Barham, 2010). Potential salt marsh habitat in the southern Puget Sound may increase by 50% as a result of these efforts, after subsided elevations accrete to historic levels (Barham, 2010). Prospective tidal swamp habitat also increased and it was expected that the dike removals would result in restored sediment transport. Restored sediment transport aids in the development of salt marsh, forested riparian, and other essential estuarine habitat structures, functions and processes. However, it remains uncertain how the Delta and its biota will respond to restoration of tidal inundation, as some restored processes may be dependent on temporally variable flood events (see conceptual model in Ellings & Hodgson, 2007).

One of the objectives of the Nisqually Estuary Restoration Project is to protect, restore, and enhance forested riparian habitat in the Nisqually River Delta, which will provide foraging and breeding habitat for migratory and resident landbirds and fish (USFWS, 2005). The desired future condition for riparian habitat is a mature forest with characteristics including: vegetation age diversity; native plant species composition and vegetation layers; and abundance of snags and woody debris (Ellings, 2008). A mature bottomland forest will take decades to develop, and in order to speed up forest succession, woody plantings were installed in areas thought to be able to develop into tidal freshwater swamps. However, a broad scientific knowledge base was still lacking, regarding functions and processes of tidal swamps (Conner, et al., 2007).

The restoration team lacked complete background information on which factors controlled the establishment of woody vegetation in a restored tidal freshwater wetland (Barham & Sampselle, NNWR, personal communication). Without that base knowledge, and with limited time and resources, it was difficult to know whether conditions in specific areas were appropriate for woody plantings. Land managers planted the tidal freshwater wetlands with woody trees and shrubs, using multiple remnant (never been diked) tidal freshwater wetlands on the Nisqually River as reference sites (Barham, 2010).

At the Nisqually Indian Tribe's Braget property, on the east side of the river, the tidal freshwater/riparian floodplain forest restoration portion consisted of two phases of plantings, totaling 53 acres. Prior to each planting, the pastured site was mowed and given a broad-spectrum herbicide application on the herbaceous regrowth. Also, the 2007-2008 planting areas were tilled (Barham & Sampselle, pers. comm.). A mixture of container, bare root and live stake (all willows were live stakes) plants were installed on 24 acres during the fall-winter of 2007-2008 and on 29 acres during the fall-winter of 2008-2009 (Table 2). All plants were installed with plastic plant protector tubes to reduce herbivory and to protect the plants during subsequent herbicide applications (Barham, NNWR, pers. comm.). See Appendix A for a full list of plants installed at the Braget property (Table 7).

The NNWR site, on the west side of the Nisqually River, was managed as a freshwater wetland prior to restoration. Concurrent with dike breaching, some of the tidal freshwater forest sites were enhanced by adding 95,040 yards^3 of fill to increase the elevation (Barham, pers. comm.). No fill was placed in the specific areas of the dike footprint analyzed in this study. The fill was surplus sands excavated from a berm outside the dike (potentially saline) during dike removal. Since this salty, very coarse material would likely not support woody plant growth, 66,065 yards^3 of topsoil was salvaged from the site prior to placing the fill and then spread on top of the imported fill to an average depth of 0.33 m. This higher elevation was expected to provide physical conditions necessary to support riparian habitat, as based on elevation surveys at nearby reference sites (Barham, pers. comm.). The restoration site was contoured to slope slightly to the northwest and to drain fully at lower tides. A constructed low swale now runs from the Nisqually River through the planting area, increasing freshwater influence at high tide (Barham, pers. comm.).

Land managers utilized excess woody debris from the removed dikes to create mulch. The mulch was installed across the planting area with some skips and gaps, creating a variety of microhabitats and microtopography (Barham, pers. comm.). Trial bare root and live stake (all willows were live stakes) native tree plantings were installed in the winter of 2009-2010 based off of the nearby reference community. Additional areas further from the river and at higher elevations were planted with bare root and live stake plants in 2010-2011, after determining how the prior year's planting had performed (Barham, 2010). None of the plants were installed inside plant protector tubes. See Appendix A for a full list of plants installed at the NNWR (Table 8).

Site	Stock Type	Species	Source	Source Location
Braget	live stake	willow spp.	harvested by crew	near the shoreline (Thurston County)
Braget	live stake	willow spp.	Sound Native Plants	Olympia, WA
Braget	container	deciduous spp.	vars. nurseries	Washington State
Braget	bare root	deciduous spp.	4th Corner Nursery	Bellingham, WA
Braget	bare root	deciduous spp.	WACD Plant Materials Center	Skagit County, WA
Braget	bare root	conifer spp.	WACD Plant Materials Center	Skagit County, WA
Braget	bare root	conifer spp.	WA DNR	South Puget Sound lowlands (below 305 m elevation)
NNWR	live stake	willow spp.	harvested by crew	near the shoreline (Thurston County)
NNWR	bare root	deciduous spp.	4th Corner Nursery	Bellingham, WA
NNWR	bare root	deciduous spp.	WACD Plant Materials Center	Skagit County, WA
NNWR	bare root	conifer spp.	WA DNR	South Puget Sound lowlands (below 305 m elevation)

Table 2: Source, stock type and source location for all restoration woody seedlings installed within the two sites.

These land management and restoration decisions, in addition to site history and each site's physical location (the NNWR plantings are adjacent to a freshwater channel, tidal marshes and mudflats, whereas the Braget plantings are adjacent to uplands, a dirt road and tidal marshes) result in significant differences in soils and hydrology. Restoration plants on both sides of the river were installed to initial mixed mortality and vigor (Barham and Sampselle, pers. comm.). At the NNWR, first year survival and initial planting density was measured using the belt transect method. For the 2010 plantings, survival was 53% on the dike footprint (measured planting density of 9.7 m^2/plant), 74% on the north bench areas without mulch (planting density of 2.4 m^2/plant), and 63% on the north bench areas with mulch (planting density of 2.9 m^2/plant) (Barham, pers. comm).

Based on quantitative and qualitative observations of planting success, land managers believed that changing environmental processes resulting from the hydrologic restoration (tidal flooding) were correlated with woody plant vigor and mortality. Not knowing exactly where plants would survive, they intentionally over-planted into marginal areas in order to determine environmental limits (Barham, pers. comm.). Some plants in the trial year may have been (purposefully) planted at too low of an elevation, resulting in high levels of inundation for woody species (Barham and Sampselle, pers. comm.).

Study Objective

The overarching question of this study is: what is the relationship between restored tidal processes and the establishment of native woody plant species in Nisqually Delta freshwater tidal swamps? The objectives of this field research are:

i) To quantify the survivorship, cover and vigor of installed woody plants in the forested tidal freshwater wetlands of the Nisqually Delta.

ii) To quantify the restored environmental conditions, including elevation, soil salinity, depth to water table, soil organic matter, bulk density and soil texture.

iii) To assess the relationship between environmental conditions and woody plant establishment.

iv) To determine whether there are measurable environmental conditions under which specific woody species do not establish.

Overall, the goal of this research study is advance the efficacy of future tidal forested restoration projects by gaining an understanding of processes within the Nisqually River Delta (Ward, et al., 2001).

Methods

Study Location

Climate

The Puget Sound region (consisting of parts of western Washington and British Columbia) has a marine climate with mild, wet winters and warm, dry summers. This maritime climate is characterized by long periods of cloudy cover and an extended frost-free season. Diurnal temperature fluctuations are narrow. The mean minimum temperature in Olympia in January is 0.11°C and the mean maximum temperature in August is 25.0° C (NOAA, 2004). During the growing season of April through September, average precipitation is 29.4 centimeters, about 23% of the total annual precipitation of 129.0 centimeters. Only 4% of total annual precipitation occurs during the hottest growing months of the year, July and August (NOAA, 2004).

Geomorphology

The Nisqually River Delta was formed in a topographic depression in the Puget Trough during the final uplift of the Cascade and Olympic mountains, 11 million years ago. Over the past two million years, repeat glaciation of the area produced the accumulation of large amounts of lacustrine and outwash sediment and a deepening of the northern part of the Puget Trough. Additional large pulses of sediment were provided by lahar flows off the slopes of Mt. Rainer (Pringle and Scott, 2001). Since the most recent glaciation event (the Vashon Stade, 14,000 years ago), the Nisqually River has cut a deep valley into its floodplain (Burg, et al., 1980). This steep walled, north-south oriented valley ranges from one to three km wide, concentrating fluvial sediment into a narrow zone (Barnhardt & Sherrod, 2006).

The formation of the Nisqually delta as we know it today began about 6,000 years ago, when sea levels reached their current levels. Over the past 6,000 years, the delta migrated northward by at least 2.4 km (Burg, et al., 1980). It is posited that about 1,100 years ago, a large earthquake in south Puget Sound resulted in at least one meter of ground subsidence within the Nisqually River Estuary (Sherrod, 2001). This is evidenced in buried forest soils underneath salt marsh peat, and dramatic changes in seed and diatom accumulations (Sherrod, 2001). The estuary is now composed of alternating layers of silt, sand and clay to a depth of 42 m (Carver & Stroh, 1970). Distributary channels within the lower delta plain periodically move positions as sediment accumulates at the mouth of the river (Barnhardt & Sherrod, 2006).

Hydrology

The Nisqually River drains a watershed of over 800 km^2 of the southern Cascade Mountains. Its headwaters are located on the slopes of Mount Rainier with a down channel distance of approximately 116 km to the river mouth. Flowing west and descending steeply in the upper watershed, the Nisqually River changes direction to flow north in the Puget lowlands (Williams, et al., 1985). The Nisqually River empties into the Nisqually Reach, which is a major, U-shaped reach in south Puget Sound. The Nisqually Reach has a recorded maximum tidal range of 6.09 m (Pentcheff, 2000). The north flowing, fresh water of the river meets the bi-directional, east-west tidal flow of the Nisqually Reach, forming a Y-shaped hydrologic confluence (Barnhardt & Sherrod, 2006) (Figure 3).

There are two smaller streams that flow parallel to the main river channel within the margins of the river valley; Red Salmon Creek to the east and McAllister Creek to the west (Barnhardt & Sherrod, 2006). The water bodies discharge directly into Puget Sound, as opposed to a protected bay. This results in a tidal dominated system under normal river flows. The strong Puget Sound tidal currents are responsible for the majority of sediment transport, with some sediment provided by the river (Barnhardt & Sherrod, 2006).

Other important drivers of site hydrology and sediment transport are the two hydroelectric dams on the river, owned by Tacoma Power. The Alder Dam and the LaGrande Dam are located in the upper reach of the river at river kilometers 68.40 and 71.13 respectively. These dams regulate downstream discharge, effectively altering the natural flow regime of the river and trapping sediment upstream (Whiley & Walter, 1998). Dams also prevent large pulses of water, called spates, from flushing tidal wetlands (Kentula, 1996). As a result, the lower Nisqually River is currently a sediment poor system, only receiving influxes of sediment when there is a flood. During flood events, in areas along the river where dikes have been removed, the restored land can now receive sediment deposits (USFWS, 2005).

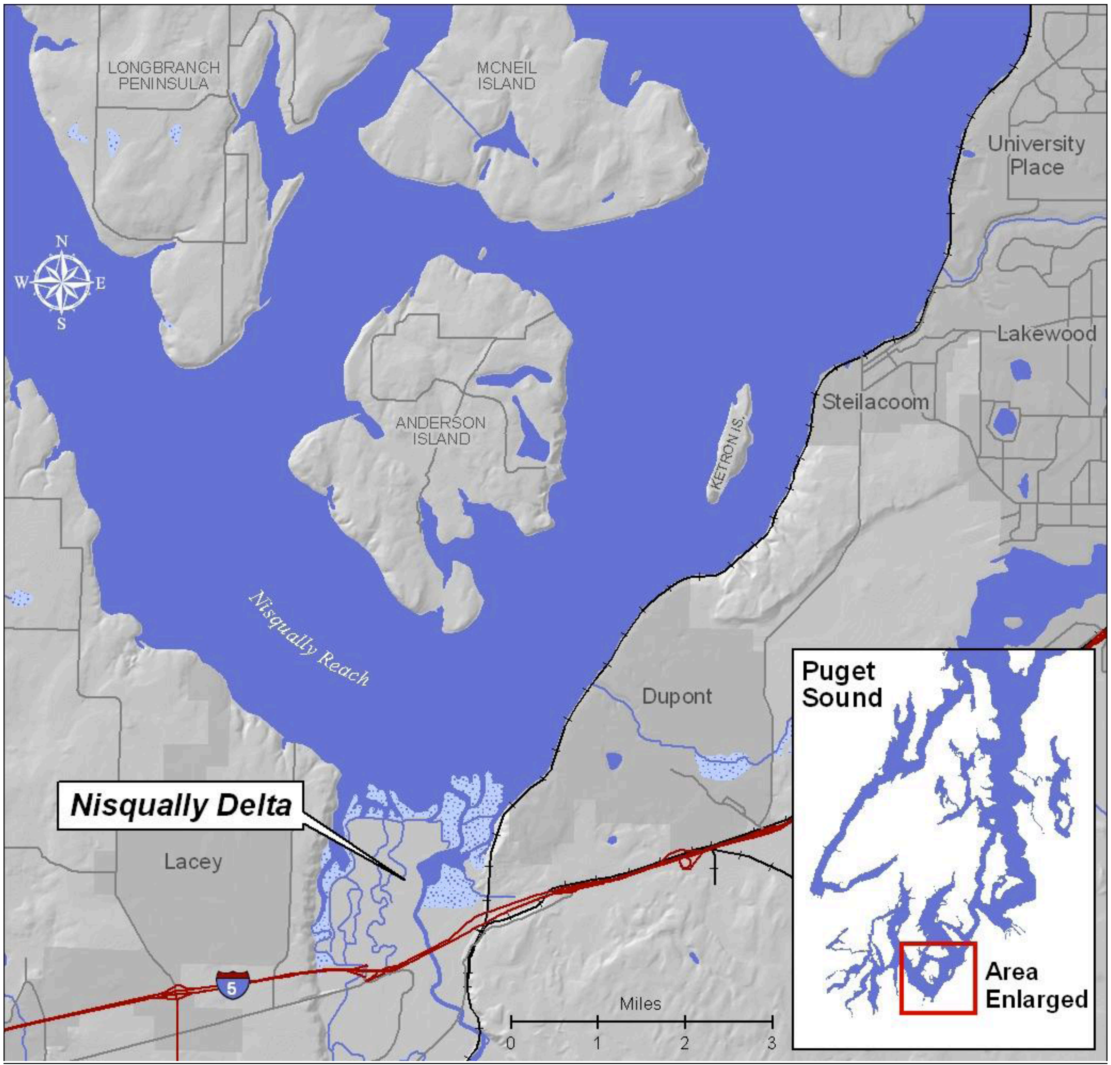

Figure 3: Location of Nisqually Delta within Puget Sound.

Reference Ecosystems

In the late 1970's, Burg et al. conducted a vegetation survey of the Nisqually River Delta (1980). They cataloged the plant associations in four ecotypes outside of the dikes and levees: sandy, high salinity, low intertidal marsh; sandy, low salinity, low intertidal marsh; sandy, high intertidal marsh; and forested wetland. See Appendix B for a complete list of recorded dominant and minor woody species found in the tidal freshwater forested wetland. They describe the tidal freshwater wetland thus:

> "The forested wetland is a forested riparian region along the Nisqually River which is infrequently influenced by tidal waters. Soils are sands and silty-sands. The

overstory is relatively homogeneous, co-dominated by *Populus balsamifera ssp. trichocarpa* and *Alnus rubra*. Two major communities can be distinguished, based on understory dominance. The first is dominated by *Symphoricarpos albus*, the second by *Rubus spectabilis*." (Burg, Tripp, & Rosenberg, 1980).

Approximately a decade later, Caicco found that the reference site was flooded during high tides and storm events with a water table close to the surface. He recorded salinity levels that were low (freshwater) to brackish (1989). He also assessed the vegetative communities at the remnant site and came to similar conclusions as Burg et al. (1980). Caicco describes this tidal area as consisting of deciduous forest with some mixed deciduous/coniferous portions (species list in Tables 9 and 10).

Black cottonwood (*Populus balsamifera ssp. trichocarpa*), big leaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*) dominated the canopy with two separate dominant shrub layers; one of common snowberry (*Symphoricarpos albus*) and the other of salmonberry (*Rubus spectabilis*) (Caicco, 1989). Also of note were willows (*Salix spp*.), vine maple (*Acer circinatum*), red-osier dogwood (*Cornus sericea*), Oregon ash (*Fraxinus latifolia*) and red elderberry (*Sambucus racemosa*) (Caicco, 1989).

The soils, elevations, salinities and plant community compositions of this reference site (along with others in the lower river) were used, with reservation, to inform restoration design decisions. Land managers were aware that the reference sites available to guide vegetation selection were not ideal sources of information, for a multitude of reasons. The reference ecosystems developed under a disturbance regime that included diked conditions, leading to highly altered salinities and connectivity. Also, the hydrology of the reference ecosystems was drastically changed by the dike removal restoration.

Sampling Design

Over the course of the 2011 growing season, data were collected on the vigor, survivorship and growth of installed woody restoration plantings in (presumed to be) hydraulically restored tidal freshwater wetlands. Caitlin Guthrie collected data, with assistance provided by Jesse Barham, Michael Moy and Laura Hurson between April 14th and October 13th, 2011. Study sites were selected based on areas of tidal influence where restoration plantings were installed between the years of 2008 and 2010. On the west side of the river, at the Nisqually Indian Tribe's Braget property, study plots were located within 29 acres planted in the winter of 2008-2009. On the east side of the river, at the NNWR property, study plots were located within 11.1 acres planted in the winter of 2009-2010.

Within the restoration planting areas, sample design was conducted systematically with a random start based off of methods described in Roegner et al. (2009). This design had the intention of achieving results that were representative of the conditions at each site. Baselines were established along each discrete planting area, using original planting plans and initial measurements of elevation as guides. Plots were spaced equally along each baseline with a randomly selected starting point.

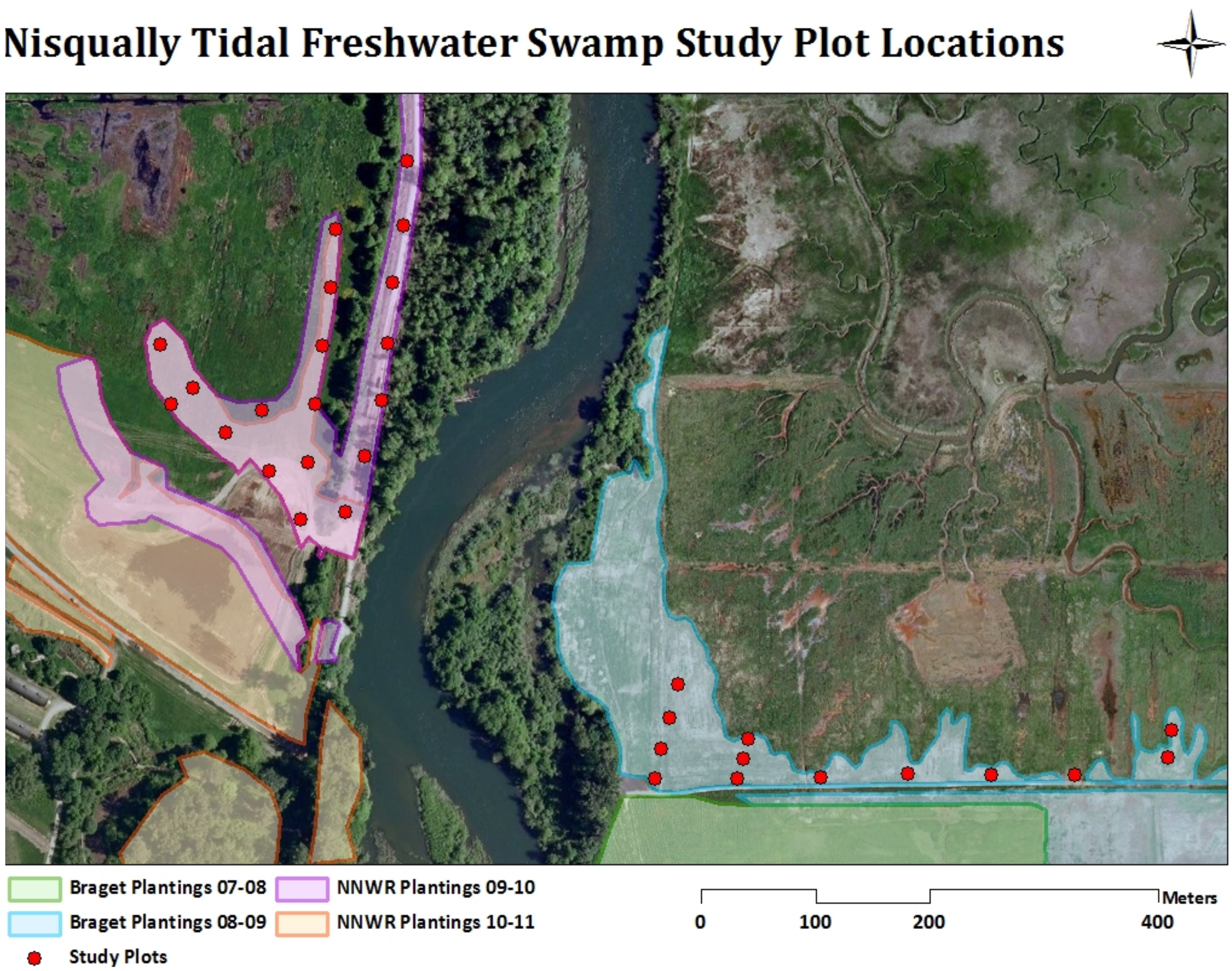

Figure 4: Map of study plot locations. The northwest grouping of plots consist of the NNWR site and the southeast groupings of plots consist of the Braget site. The Nisqually River runs south to north between the two study locations.

At the Braget site, 17 plots were located 50 m apart along an east-west oriented baseline. The restoration plantings of interest were focused close along the north side of the road through the site (Figure 4). In order to increase sample size, in areas where the plantings extended to the north, additional plots were installed along secondary transects. These plots were located a variable distance apart from each other, with locations chosen based on differences in elevation or in herbaceous vegetation composition (under the assumption that distinct herbaceous layers may represent differences in environmental factors, such as soil salinity, organic matter content and pH).

At the NNWR site, 14 plots were located 75 m apart along three separate baselines. Plots were located 75 m apart instead of 50 m as at Braget, due to funding limitations on overall sample size and in order to keep sample sizes at the two sites similar. Three lines were necessary in order to access the full extent of the restoration plantings. Plots were located on the line or to the east or west (up to 5 m from the baseline) in order to ensure data represented the full range of planted elevations. Plots were located in the dike footprint and north bench areas (Table 8).

The ends of each baseline and every plot were marked with semi-permanent stakes and recorded via GPS. Each established plot consisted of a 10 m diameter circle. Within each plot all woody plant individuals were identified and recorded for mortality and seasonal growth, as measured by change in stem basal diameter during the 2011 growing season. Temporary monitoring wells were installed in each plot to measure pore water salinity and depth to water table. These data were collected semi-monthly, along with soil moisture. Singular measurements were taken from each plot on environmental factors, including elevation, soil texture, soil percent organic matter, soil pH and soil bulk density. All measurements were taken at low or slack tides for consistency and for ease of accessibility to sampling sites.

Vegetation Sampling Scheme

The success of native vegetation plantings can be determined by assessing survival and growth of the plantings over time (Roegner, et al., 2009). In this study, we considered four response variables: survivorship, vigor, initial basal area and change in basal area over the course of the 2011-growing season (see Table 11 in Appendix C). These variables are included to cover a wide range of ways to define restoration planting "success".

In mid-April 2011, prior to the growing season, woody plants within each plot were identified to the species level, and recorded with regard to mortality, vigor and growth. A total of 25 different tree and shrub species were installed in the study area. Since willows often hybridize, making visual identification difficult, many willows were not identified to the species level. All plants were noted as installed or volunteer. In October 2011, at the end of the growing season, all measurements were repeated per plant. Species not commonly found were left in the analysis (volunteer plants were deleted), as the plants were purposefully installed into the site. For purposes of analysis, data were compiled from all installed plants within each plot to result in plot-level summarized values.

Installed species density at the NNWR site was 0.31 plants/m^2, whereas measured density inside the study plots was 0.27 plants/m^2. Installed species density at the Braget site was 0.19 plants/m^2, whereas measured density inside the study plots was 0.20 plants/m^2. This confluence of densities, in conjunction with the fact that the Braget site plants were installed inside protection tubes, indicates that the overwhelming majority of installed plants within each plot were accounted for in the study.

Survival rates were calculated for both survival since installation and seasonal survival. To determine survival rates, we recorded the number of live and dead plants per plot in both April and October, 2011. In the following statistical analysis, survival rates since installation were used. By using this metric, factors that may have killed the plant soon after planting are taken into account. The following formula was used to calculate plot survival rates in both April and October. Using the October values for the "number dead" in the below formula resulted in the overall survivorship. Subtracting the proportional survival rate calculated for April from the proportional survival rate calculated for October resulted in the seasonal survival rate:

$$\frac{\text{total planted} - \text{number dead}}{\text{total planted}} * 100 = \%\ \text{survival rate}$$

Initial basal area and change in basal area represent plant growth, and were calculated based on the measurements of basal stem diameter taken on every installed plant at the beginning and end of the growing season. Since the majority of plants were less than two meters tall, basal diameter was measured with calipers at 10 cm above the ground using a standardized methodology (Wentworth, et al., 2008). The following formula was used to calculate basal area per plot:

$$\sum \quad \left(\pi \left((\text{diameter cm})/2 \right)^2 \right) \times \frac{1\ \text{dm}^2}{100\ \text{cm}^2} = \text{basal area decimeter}^2$$

Using the above formula, the area of each stem was calculated and converted to area in square decimeters. Square decimeters were used instead of the standard square meters, because this study's values of basal area in square meters were exceptionally small, generally between 0.0001 and 0.0009 m^2.

To calculate proportion change in overall basal area, initial basal area (April, 2011) was subtracted from the final basal area (October, 2011) per plot, and then was divided by initial basal area. Only live plants were included in the calculations of initial and final basal area. With the high mortality levels present on some of the plots, this resulted in some plots with negative changes in basal area, as the growth of the surviving plants did not exceed the initial basal area of plants that died during the year.

To capture different stages of growth, height of the tallest stem was measured for all installed plants, at the beginning and end of the study. However, observations in the field indicated high browse levels by black-tailed deer on select species, resulting in apparently negative growth rates. Whereas herbivory is an important factor to take into account for most restoration plant installations, it is not one of the variables examined in this analysis. For this reason, stem height variables were left out of the data analysis.

An ordinal vigor classification was assigned to each installed plant at the beginning and end of the growing season (Table 3). Since one of the goals of this analysis was to pull out the explanatory variables relating to overall success of the installed species, and not to examine differences between the beginning and end of the growing season, we did not look at the change in vigor over time. Instead, the vigor classifications for the beginning and end of the growing season were summed and averaged by plot. This standardization method was chosen over other ordinal standardization methods – such as analyzing class change or mode – in order to best serve the research questions. However, calculating average values for vigor decreases the meaning that one is able to take out of the final values, since these ordinal classes are subjective and not equal distance from each other.

Vigor	Ranking	Description
High	3	Plants exhibiting remarkable growth and vigor.
Medium	2	Plants exhibiting moderate growth and vigor and expected to live beyond the immediate growing season.
Low	1	Plants expected to die within the year.
Dead	0	Plant is dead.

Table 3: Woody plant vigor categories assigned to each plant at the beginning and end of the 2011-growing season.

Environmental Variable Sampling Schemes

In addition to the woody plant data (response variables), numerous potential explanatory variables were compiled as well.

Elevations and Datum

Elevation surveys of the plots were conducted by Jesse Barham (NNWR) and Caitlin Guthrie (University of Washington) on June 14th, 2011 using a survey grade Real Time Kinematic (RTK) GPS unit (Leica Viva). Elevations were tied to Pierce County CORS benchmarks in real-time using the cellular network to provide corrections from existing benchmarks. A measurement of elevation was taken in the center of each plot.

In the following "Results" section, plot elevations are given as either elevation above mean lower low water (MLLW) or in NAVD88. Appendix E contains plot elevations in NAVD88, MHHW and MLLW. NAVD88 is a fixed geodetic datum, and is the official vertical reference datum for the U.S.A. (Gill & Schulz, 2001). MLLW and MHHW are both tidal datums. This means that their values are not absolute, instead they vary spatially and temporally according to changing land levels (subsidence or accretion), winds, currents and changing sea levels. Therefore, the relationship between a geodetic datum, such as NAVD88, and the tidal datums differs based on location and time.

MLLW is the mean elevation of the two low tides of the day, averaged over a 19-year period. MHHW is the mean elevation of the two daily high tides. In tidal restoration projects, tidal datums, specifically MLLW, are necessary in order to interpret the hydrology of a site. MLLW and MHHW give elevation values that can be reliably and mathematically related to inundation regimes (Brophy, 2009). Tidal forested wetlands are often located near or above the highest extent of tidal inundation. To understand and design for their inundation regimes, MHHW is an instrumental reference point (Brophy, 2009).

It is most accurate to calculate MLLW and MHHW measurements based on local tidal records. Lacking sufficient local tidal data, I utilized the NOAA program Vdatum to convert elevation between water level data and the measured land elevation data (NOAA, 2011a). Data conversion was provided by Kelly Turner (USGS) with technical support provided by Jesse Barham (NNWR). Elevations were checked against tidal data from the Dupont Wharf prediction station, located a few kilometers northeast of the Nisqually Delta (NOAA, 2009).

Depth to Water Table, Soil Pore Water Salinity and Soil Moisture

Depth to the water table, salinity, and soil moisture measurements were taken semi-monthly for a total of 11 dates over the course of the growing season, as close to the daytime low tide as possible. Due to the challenge of visiting all 33 sites during low tide, some time series measurements were collected during slack tide. Temporary, shallow (76 cm long x 2.5 cm wide) PVC pipe monitoring wells were installed with an auger in the center of each study plot to measure pore water salinity and depth to water table. Soil salinity measurements were taken with a handheld refractometer from water within the well, using 1 ppt (approx. 1mS/cm conductivity) as the accuracy and precision standard for salinity. The volumetric water content, or soil moisture, was determined by oven drying the samples to constant mass in a drying oven at 105°C and using the following formula (ISO 11465, 1993):

$$\%\ \text{water content} = 100 \times \frac{\text{soil mass wet (g)} - \text{soil mass dry (g)}}{\text{Soil mass dry (g)}}$$

Soil Texture, pH and Percent Organic Matter

Soil subsamples were collected with a hand trowel at three random locations from the top 20 cm of the soil surface in each plot. This depth contains the fine root zone for most vascular plants (Brophy, 2009). Soil samples were analyzed at the UW Soil Science Laboratory and the UW Plant Ecophysiology Laboratory, whose existing QA/QC protocols are designed to prevent sample identification error. The three samples from each plot were thoroughly mixed and passed through a two-mm screen. Samples were dried at 105°C for 12 hours. Portions of the sample were extracted in the lab for the three analyses. pH was measured in 1:1 water (McLean, 1982). Percent organic matter was determined by loss on ignition at 360°C in a muffle furnace for three hours (Schulte & Hopkins, 1996). Soil textural analysis (percent clay, silt and sand) was determined using the hydrometer method (ASDM, 2002). The results of the hydrometer readings were entered into a series of equations to relate the diameter of particles to the rate at which they fall out of suspension, to determine sand, silt and clay proportions.

Soil Bulk Density

One sample for bulk density was collected from the center of every plot. After clearing away organic matter, the core method was used, with a hammer auger of 5-cm diameter and six interior rings (AMS Inc, American Falls, ID). The bottom and top ring were cut off, leaving the middle four rings with a known volume. All samples were desiccated in a drying oven at 105°C for 12 hours. Dry weight was taken for each sample and divided by the volume, to provide an estimate of bulk density (ISO 11272, 1993).

Herbaceous Cover

Herbaceous cover was quantified at both the beginning and end of the growing season. The percentage of each plot occupied by herbaceous species was recorded, using the Daubenmire Cover Class breakdown (Table 4) (Roegner, et al., 2009). By collecting data on the herbaceous layer, we could identify potentially competing vegetation and indications of site conditions. Plot level observations were also taken on potential causes of plant mortality, animal activity, mulch presence, and other items of note.

Class Cover	Percent Cover
1	0 – 5%
2	6 – 25%
3	26 – 50%
4	51 – 75%
5	76 – 95%
6	96 – 100%

Table 4: Daubenmire herbaceous cover class categories assigned to each plot at the beginning and end of the 2011 growing season.

Analytical Methods

Data Preparation

Three of the explanatory variables collected were in the form of a time series (collected semi-monthly over the course of the growing season, for a total of 11 dates). These variables were soil moisture, pore water soil salinity and depth to water table. Since the objective was not to examine these factors over time, but to instead most accurately represent conditions over the course of the growing season, these data had to be explicitly accounted for prior to statistical analysis. To interpret these repeated measures, which were not independent, the data were combined. One advantage of this technique is that it accounted for potential correlation between the time series explanatory variables.

The three time series variables from 11 dates combined to 33 variables. This dataset was reduced to three representative variables through the use of a principal component analysis (PCA) (See "Data Reduction" section for additional information on PCA tests). In addition to the conversions performed on time series data, herbaceous cover and soil texture variables were reduced to one variable each. The sum of percent silt and clay was used to represent soil texture. For herbaceous cover, the ordinal values for the start and end of the season were converted to midpoints and then averaged by plot.

The majority of explanatory variables were relativized by range for use in a Euclidean distance matrix. A relativization was used because the scale of the variables affects the calculated distances. By relativizing by range, scale becomes the same for all variables (zero to one). Explanatory variables that were relativized by range include: soil texture (% silt + % clay), elevation, PC1, PC2, PC3, soil organic matter, soil pH, soil bulk density and herbaceous competition (see Table 13 in Appendix C). Non-relativized original values were used in the regression tree analysis. All plant response variables were relativized by range for use in a Euclidean distance matrix.

Data were stored and managed in Excel, version 14.1.0 (Microsoft Co., 2004). Plant response data and environmental explanatory data were stored in separate files. All analyses were conducted in R, version 2.8.1 (The R Foundation, 2008). Spreadsheets were converted into text files prior to importation into R.

Analyses

Multivariate analyses can be used as exploratory techniques, which in this analysis permitted visualization of the variation in planting success rates based on similarities in survivorship, growth and vigor. The measurement of quantitative differences in planting success allows the delineation of environmental conditions that are appropriate for restoration plantings. The first step in data analysis following data adjustments and standardizations was to convert the response data and explanatory data into distance matrices. A Euclidean distance matrix was used for the vegetative response data. The Euclidean method was appropriate for the vegetation response data in this analysis for several reasons. First, the values representing change in basal area are represented as both negative and positive changes. The Euclidean method accepts all domains of values. Additionally, the vegetation variables are very similar to one another in scale. Finally, since the response variables analyzed are summary values representing overall species response per plot, the response matrix is dense (containing few zeros).

Data Reduction

Principal component analysis (PCA) is an ordination method that is appropriate when used to describe linear relationships between variables that are correlated. In this dataset, the soil moisture, depth to water table and salinity time series are three sets of variables that fit the limitations and goals of a PCA. The goal was to reduce the set of 33 variables collected on 11 different dates during the growing season to a smaller number of summary variables. These summary variables allowed the simplification of interpretation of environmental gradients. For these analyses, the cross-products matrix was in the variance/covariance form.

By interpreting the first three principal components (PCs) for the time series variables, we were able to explain a total of 74% of the variation in soil moisture, pore water soil salinity and depth to water table (see Table 14 in Appendix D). These three PCs are by nature uncorrelated with one another and the PCA scores were used in subsequent analyses (See Table 15 in Appendix D).

Differentiation by Site

We conducted a Multi-Response Permutation Procedure (MRPP) analysis on the plant response variables using the "Vegan" package in R, with a Euclidean distance matrix and as compared to 9,999 permutations. The purpose of this analysis was to determine whether there was a significant difference between two groups of sampling units (in this case the NNWR site and the Braget site). MRPP focuses on the statistical distance between each plot's sample units, and determines whether the mean distance within groups is smaller than the mean distance between randomly selected groups.

Multivariate Grouping of Plots

The next step in the data analysis was to determine whether there were discernible groupings of plots based off of the environmental and response variables. These groupings can yield information on ecological relationships and classify new observations, but can also obscure linear relationships (De'ath, 2002). Using a multivariate regression tree, it is possible to define a hierarchical group structure by analyzing the relationship between the response and explanatory variables (Breiman, et al., 1984).

Multivariate regression tree analysis, or CART (classification & regression trees), is most often applied when classifying habitat with compositional data. In this case, our goal was to classify tidal freshwater wetland swamp habitat, and to determine what site conditions supported the success of woody plants. However, since plants were purposefully installed, compositional data was not appropriate.

Using the "mvpart" package in R, with a Euclidean distance matrix, the model was run with all four response variables: survivorship, initial basal area, change in basal area, and vigor. A Manhattan distance measure was used for the multivariate analysis. The

Manhattan distance measure (also called "city block") calculates distance based on the sum of absolute deviations about the mean in all dimensions. For the univariate analyses, response variables were left in original form. Potential explanatory variables included PC1, PC2, PC3, site, soil OM content, average herbaceous cover, soil texture, soil pH, soil bulk density and elevation. Stopping size for the tree was set at 5 plots, aka the minimum group size that the tree would be split on was 5, and each group had to include at least 2 plots. The cross validation procedure removed a one-plot subsample from the analysis and ran 10 trials to determine the cross-validated relative error.

Whereas usually one only proceeds to univariate tests if the multivariate test is significant, in this case, it was thought to be highly likely that the diverse type of response variables were correlated to differing extents with the explanatory variables (for example newly installed trees are at high risk of salinity rated mortality, whereas vigor may be greater affected by summer drought). For that reason, univariate regression trees were run on the four response variables.

Since ecological CART analysis is typically used with compositional data, we chose to examine potential data set groupings with other analytical techniques. Hierarchical polythetic agglomerative clustering analysis was performed on the response variables (vigor, survivorship, initial basal area and change in basal area) to form groups of plots with similar traits. In this descriptive method, groups were selected based on the resulting dendrogram (McCune & Grace, 2002). It was expected that discontinuities existed in the data, with environmental thresholds at which installed woody plants do not thrive. Grouping via clustering allows us to determine the approximate threshold values. The "hclust" function in R was used for this analysis. Specifications included a Euclidean distance measure, and Ward's minimum variance method as the group linkage method (Ward Jr., 1963). In order to define groups, we used a scree plot of fusion distances versus the potential number of groups. The appropriate number of response variable groups was determined based on a sharp change in slope visible on the scree plot.

Using Nonmetric Multidimensional Scaling (NMDS), it was possible to visualize the cluster analysis. This visualization method is "a robust technique for indirect gradient analysis" and for mixed skewness (Minchin, 1987), which is appropriate for these data and research questions. We used the "metaMDS" function in R with a Euclidean distance measure, a random starting configuration, two dimensions and 40 runs.

Finally, a Distance Based Redundancy Analysis (dbRDA) was used to examine the relationship between specific explanatory variables and planting success. In dbRDA, PCA "is used to extract the principal coordinates of a calculated matrix of ecological distances… and since significance testing is by permutation there is no need for an assumption of normality" (Macdonald & Fenniak, 2007). This technique is often used in community ecology, with continuous explanatory variables to conduct a multivariate analysis of variance (Legendre & Anderson, 1999). A number of disadvantages of using dbRDA with community data do not apply to this dataset, as the response variables do not consist of compositional data. Additionally, this method assumes a linear relationship between response and explanatory variables, which is most likely the case for some of the relationships examined, but not for others.

This analysis used the "capscale" function in the "vegan" package of R, with Euclidian distance measures specified for the response variable matrix (created by PCA). The "capscale" program expresses eigenvalues in units as a fraction of the total variation, instead of the more common sum of squares. The environmental matrix contained site, elevation, PC1, PC2, PC3, soil bulk density, soil pH, soil texture, soil organic matter and herbaceous cover. Environmental variables were selected for inclusion in the model via a forward stepwise selection. All variables were tested together and a variety of potentially ecologically significant interaction terms were tested in exploratory analyses. Using 500 permutations in ANOVA, we tested the significance of the model, the axes and the environmental variables.

Results

Descriptive Statistics of Environmental Variables

Elevation

The average elevation of all plots was 4.56 meters above MLLW, with wide variation between sites, and within some of the sites, due to slope. The NNWR site averaged 4.41 meters above MLLW, whereas the Braget site averaged 4.74 meters above MLLW (Figure 5). Mean higher-high water was at approximately 4.16 meters above MLLW. Six of the plots were located below the MHHW elevation, and therefore received close to daily hydrologic inundation. The other, higher sites, received inundation at fewer high tides per month, and may have been affected by tidal groundwater response.

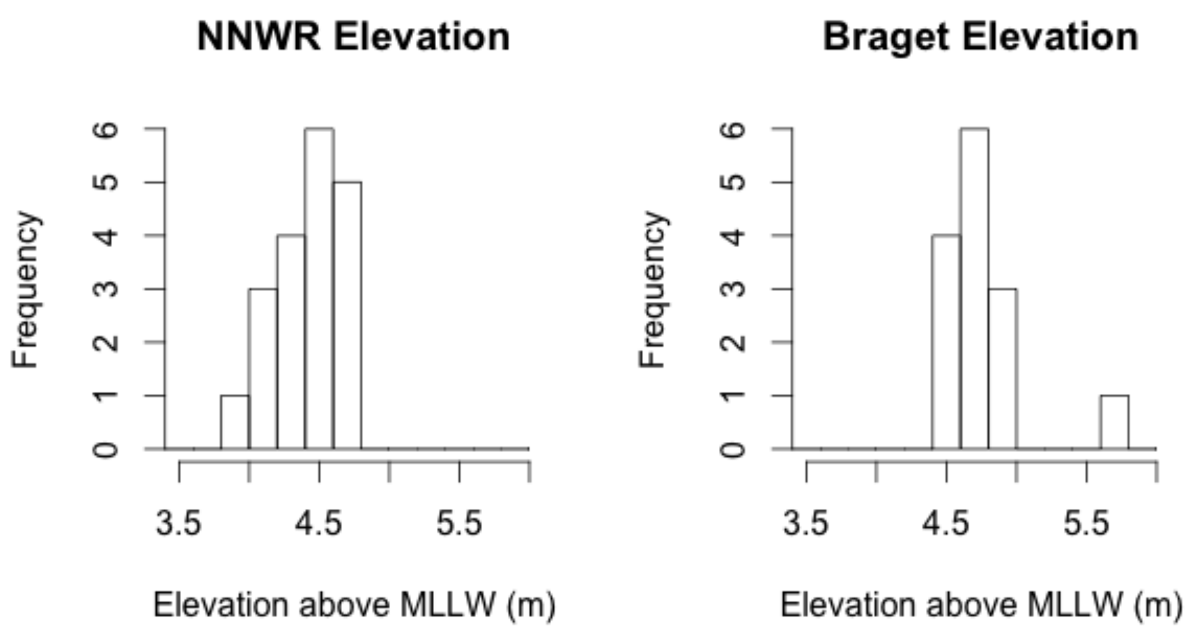

Figure 5: Histograms of elevation above MLLW, in meters, at the two sites.

Time Series Variables – Depth to Water Table, Soil Salinity and Soil Moisture

The first three PC variables were used in the data analysis. In total, they explained 74% of overall variation in the time series variables (Table 14). PC1 scores explained 32% of variation and were positively correlated with depth to water and negatively correlated with salinity. They were also, to a lesser extent, negatively correlated with soil moisture.

In other words, as depth to water increased, salinity and soil moisture values decreased.

The PC2 score explained 26% of variation and was positively correlated with soil moisture. It also had a moderate negative correlation with depth to water table and soil salinity. As soil moisture increased, depth to water table decreased, and salinity decreased. The PC3 score explained 16% of the total variation and was less strongly correlated with any specific time series. All three variables were positively correlated with PC3.

A biplot of PC1 vs. PC2 shows groupings based strongly on variable, with the three environmental variables negatively correlated with each other (Figure 6). Using this PCA model, PC1, PC2 and PC3 scores became new data points, representing the weighted averages in variability of soil moisture, soil salinity and depth to water (Table 15).

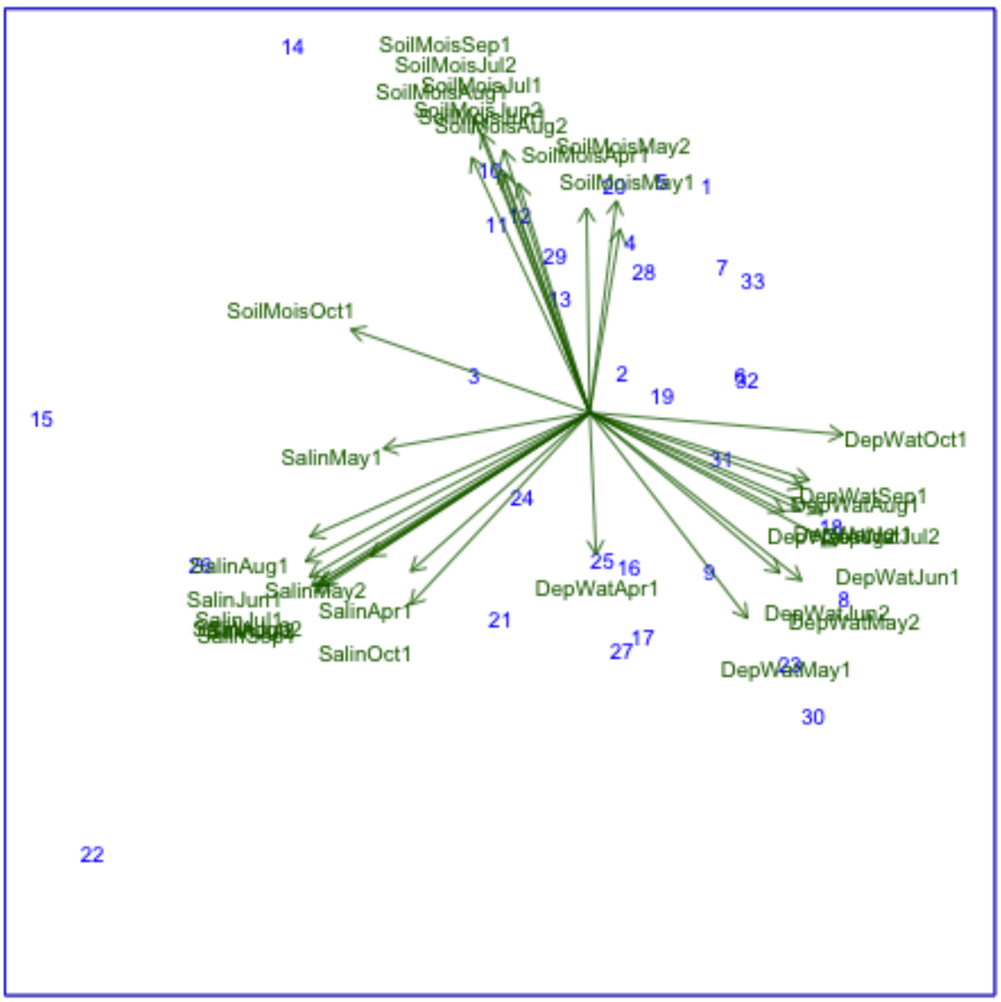

Figure 6: PCA biplot of time series data. The X-axis consists of PC1 and the Y-axis consists of PC2. The numbers represent the ordinated distance each plot was from all other plots as determined based on PC1 and PC2.

Salinity was highly variable over time and between the plots. The overall average salinity measurement was 3.2 ppt, with a mean of 4.0 ppt at the NNWR site and a mean of 2.2 ppt at the Braget site (Figure 7). The average maximum salinity measured at the NNWR site was 9.3 ppt and at the Braget site was 4.7 ppt. Average salinity was highest in October, at about 7.8 ppt, and lowest in April and May, at about 1.5 ppt. In general, among sites with positive salinities (many sites had consistent salinities of 0 ppt), salinity levels rose from spring, through summer and into autumn.

There was a strong negative linear correlation between the average daily Nisqually River freshwater discharge (U.S.G.S., 2012) and salinity levels on site (p-value = 0.007, R-squared = 0.57). As river discharge decreased, salinity levels rose (Figure 8). Pacific Northwest rivers generally have the highest flows in winter and spring, due to snowmelt and precipitation. Flows decrease into the summer. Discharge in the Nisqually River, as measured at the McKenna gauge station (located approximately at river km 24), decreased stepwise each month from an average of 2,390 cubic feet per second (cfs) in April 2011 to 940 cfs in September (U.S.G.S., 2012).

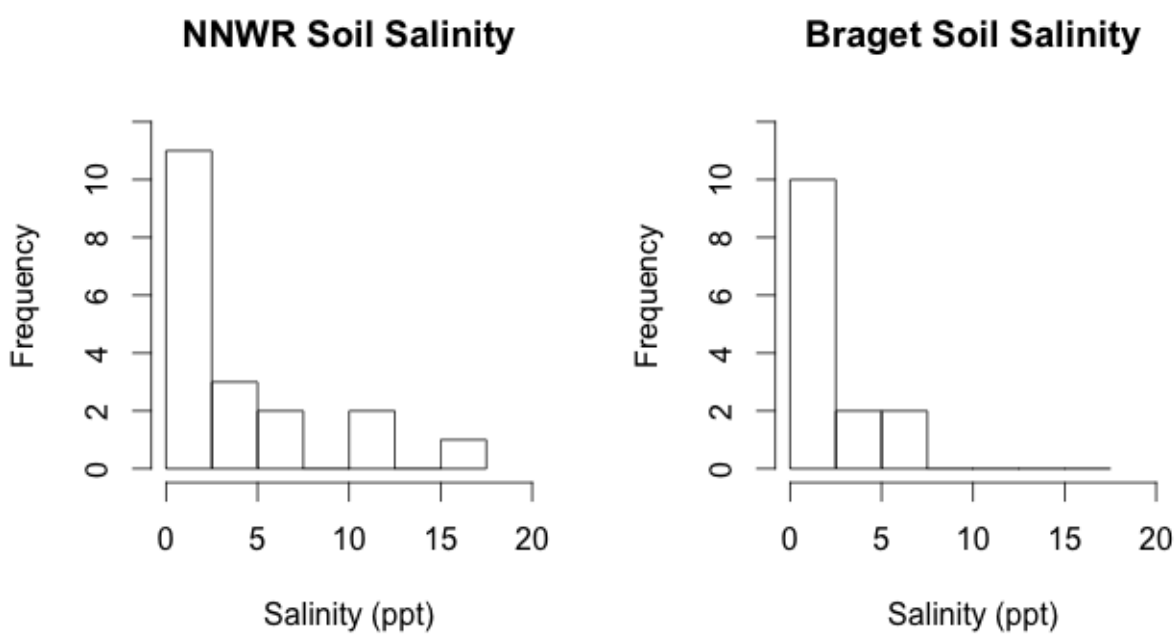

Figure 7: Histograms of soil salinity, as averaged, April – October 2011 at the two sites.

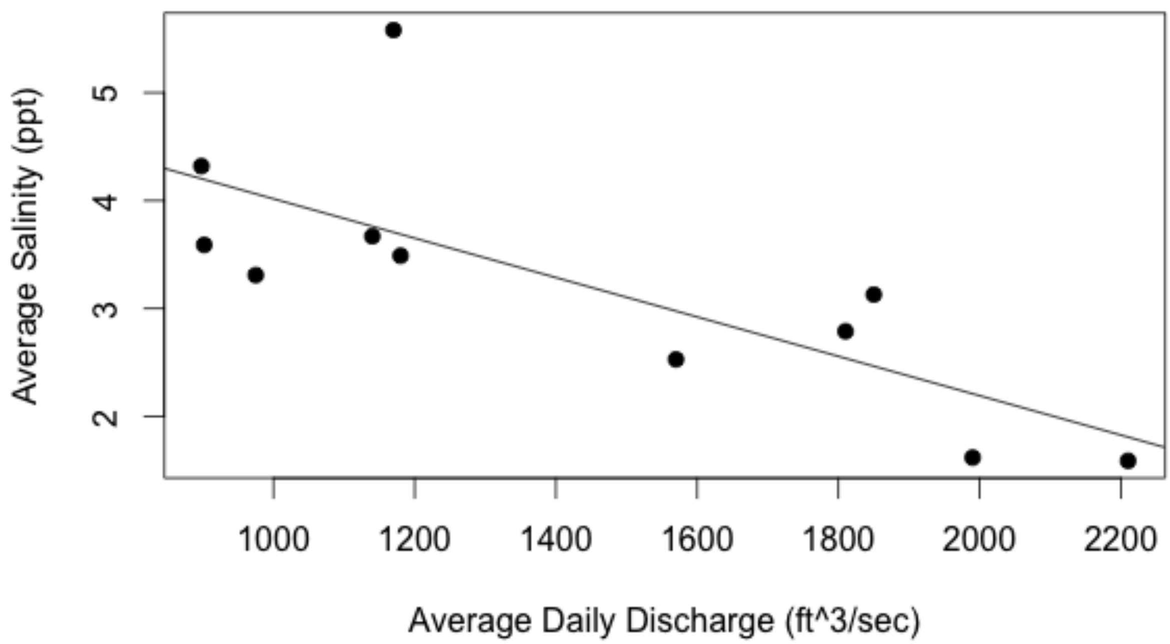

Figure 8: Time series salinity measurements as averaged over all plots, versus Nisqually River daily discharge. The upper left-hand corner outlier is from the October measurements, taken as tide was coming in (all other data taken during tidal ebb or slack).

Depth to water table was highly variable over time, and between the different plots. The overall average depth to water table was 0.50 meters below ground, with a range of 0.15 meters below ground to 0.70 meters below ground (Figure 9). (Wells did not extend past 0.70 meters below ground. If no water was found in a well, depth to water table was noted as 0.70 meters). The NNWR plots had an average depth to water table of 0.45 meters, with some plots maintaining a high ground water table all summer long. The majority of Braget plots had deeper water tables; between 0.50 meters and 0.60 meters with a site average of 0.58 meters below ground. For all plots, average depth to water was lowest in April (averaging 0.28 meters below the ground surface) and highest in late August (averaging 0.65 meters below the ground).

A linear model shows that depth to water table was significantly negatively correlated with average daily Nisqually River freshwater discharge rates (p-value = 0.003, R-squared = 0.63). As discharge rates decreased over the summer, the water table moved deeper (Figure 10). The Braget site had a greater degree of freshwater river discharge influence than the NNWR site (Braget depth to water = 81% correlation with discharge and NNWR depth to water = 57% correlation with discharge).

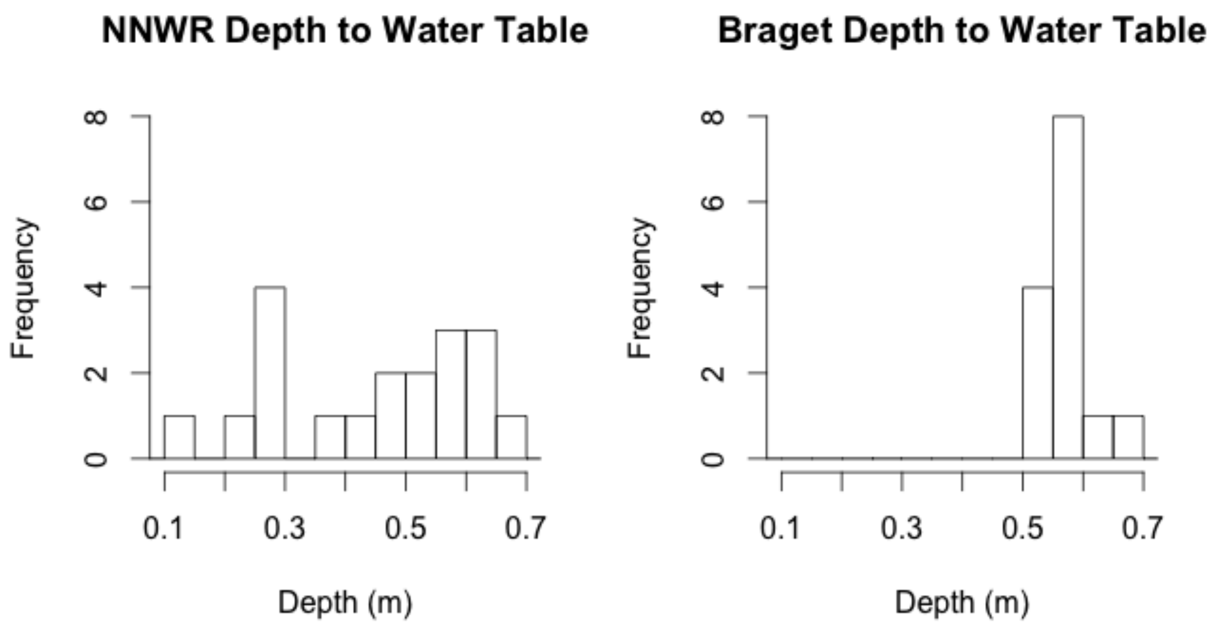

Figure 9: Histograms of depth to water, as averaged, April – October, 2011 at the two sites.

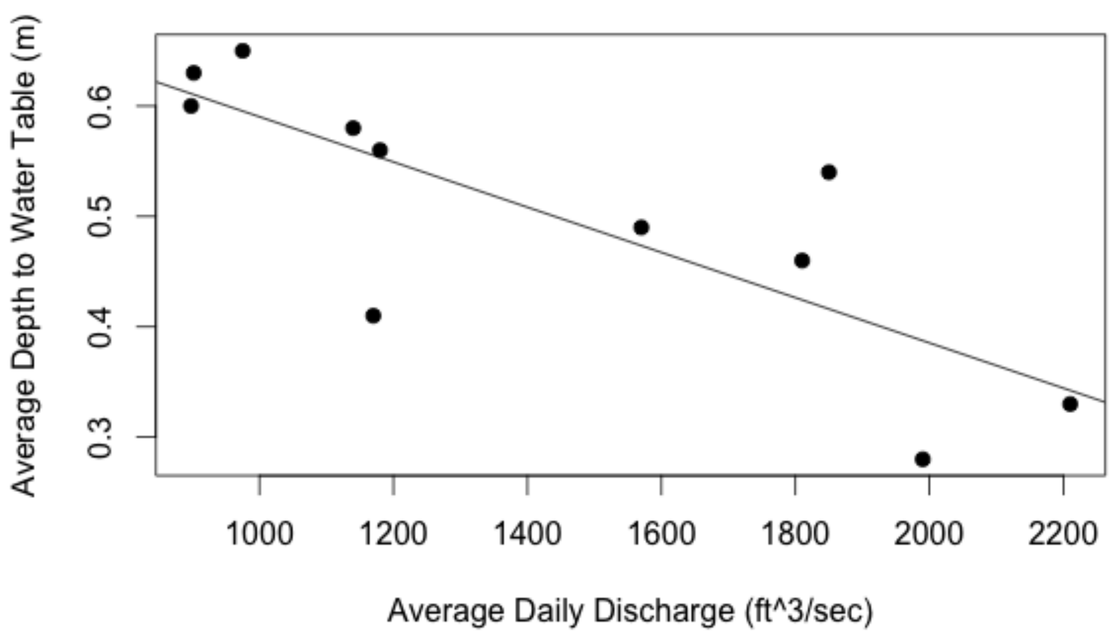

Figure 10: Depth to water table and Nisqually River average daily discharge linear model.

The range for average soil moisture per plot was 15% to 55%, with an average of 34% soil moisture in NNWR plots and an average of 42% soil moisture in Braget plots (Figure 11). Average soil moisture was highest in October (overall mean of 50% soil moisture) and lowest in early August (overall mean of 31% soil moisture).

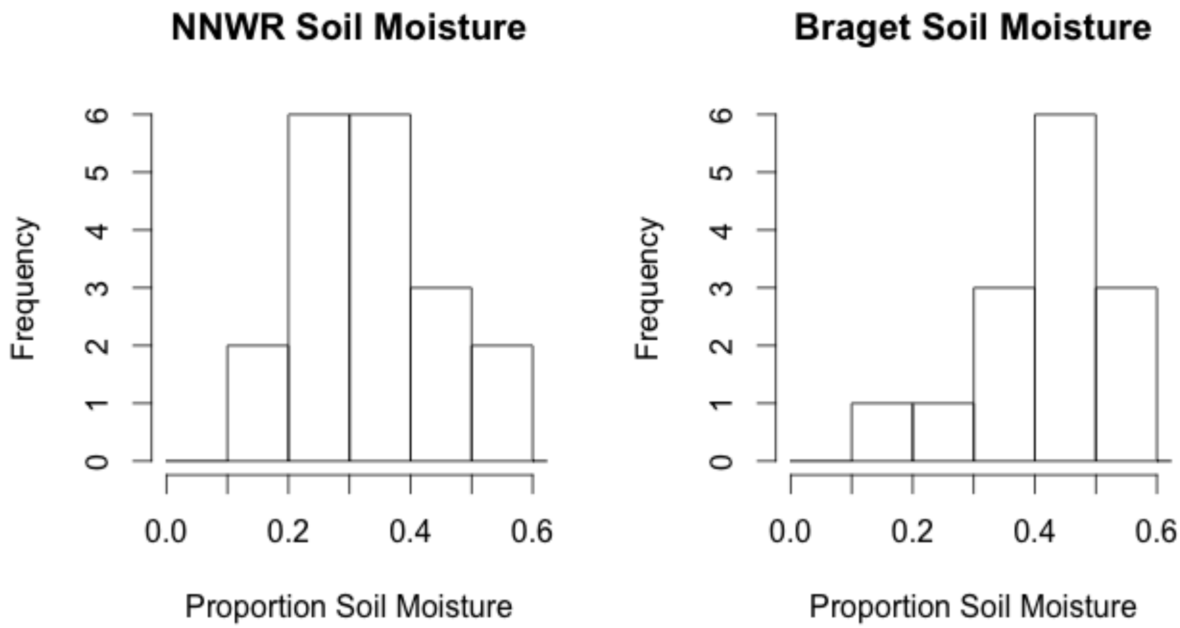

Figure 11: Histograms of soil moisture, as averaged, April – October 2011 at the two sites.

Soil Variables

The range for soil bulk density was 0.6 g/cm^3 to 1.5 g/cm^3, with an overall average bulk density of 1.19 g/cm^3. The two sites were very similar in bulk density, with 1.23 g/cm^3 as the NNWR site mean, and 1.13 g/cm^3 as the Braget site mean. These bulk density measurements are within the range of normal soils (Lal & Shukla, 2004).

Mean organic matter content within the measured plots was 7.3% with a standard deviation of 2.8%, indicating high variation between the plots. At the NNWR plots, mean organic matter content was 6.6% with a standard deviation of 2.4%. At the Braget plots, organic matter content was 8.4%, with a standard deviation of 3.1%. These organic matter levels are within the range of normal Pacific Northwest mineral soils (Sidle & Drlica, 1981).

The pH levels of the soil at the two sites varied greatly from each other. The overall range in soil pH was 3.7 to 5.8, with an average of 4.8 (Figure 12). The NNWR site ranged from 3.7 - 5.2 and a mean soil pH of 4.4, whereas the Braget site ranged from 4.8 - 5.8 with a mean soil pH of 5.4. These values are within the normal range for coastal soils (Sposito, 1989). Four sites at the NNWR, on the dike footprint, exhibited an extremely acidic pH under 4.0, indicating the presence of free acids. The majority of sites had an acidic pH under 5.5.

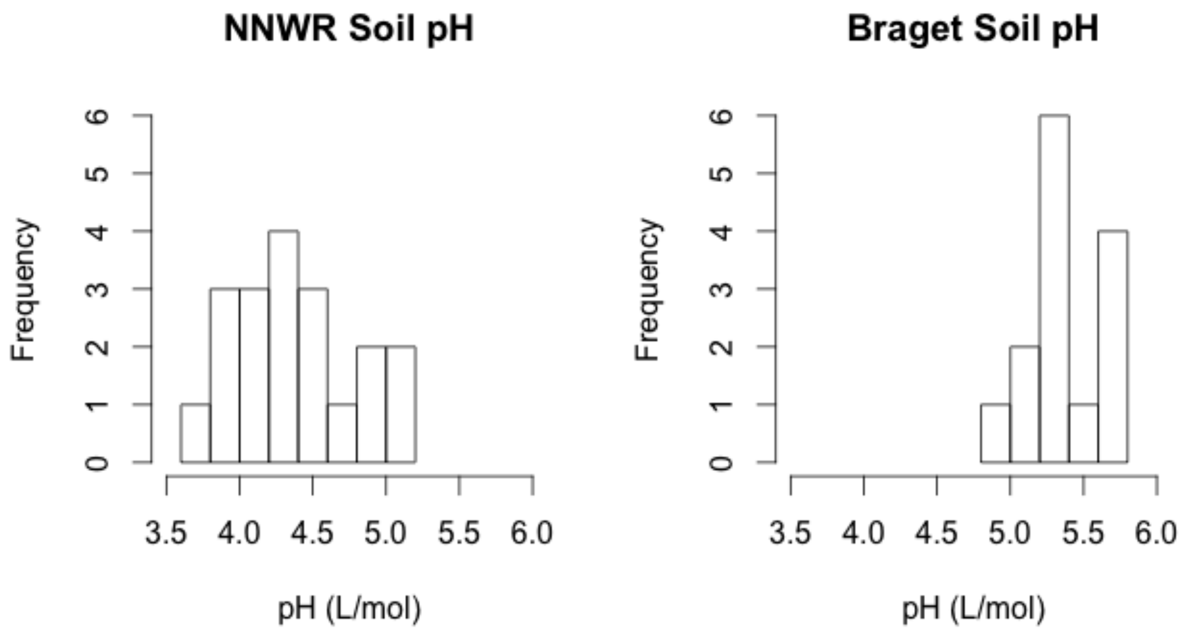

Figure 12: Histograms of soil pH at the two sites in L/mol.

Grain size analysis indicated that the majority of plots were dominated by sand (particle diameter of 0.05 mm to 2.0 mm), with an overall range in sand content of 37% to 90%. Silt (0.05 mm to 0.002 mm) content of soils at the two sites varied from 6% to 40%. Clay (particles smaller than 0.002 mm) content of soils of the four sites varied from 1% to 15%. The NNWR site had 14 plots that classified as sandy loam and one plot each classified as loam, sand, loamy sand, and silt loam. The Braget site had nine plots classified as sandy loam and five plots classified as loamy sand. Soils dominated by sand-sized particles, such as these, have large pores and rapid soil aeration and water percolation. However, sand does not have a high capacity to hold water or nutrients and may be droughty and infertile.

Herbaceous Cover

Herbaceous cover was averaged between an early season and a late season measurement, and was highly variable between the two sites (Figure 13). The NNWR site had an average cover level of “4”, corresponding to a range of 51% to 75% ground cover (see Table 4 for qualitative cover classes), and had high within site variation in herbaceous cover. The Braget site had an average cover level of “6”, corresponding to a range of 96% - 100% ground cover. There was very low within site variation between Braget plots.

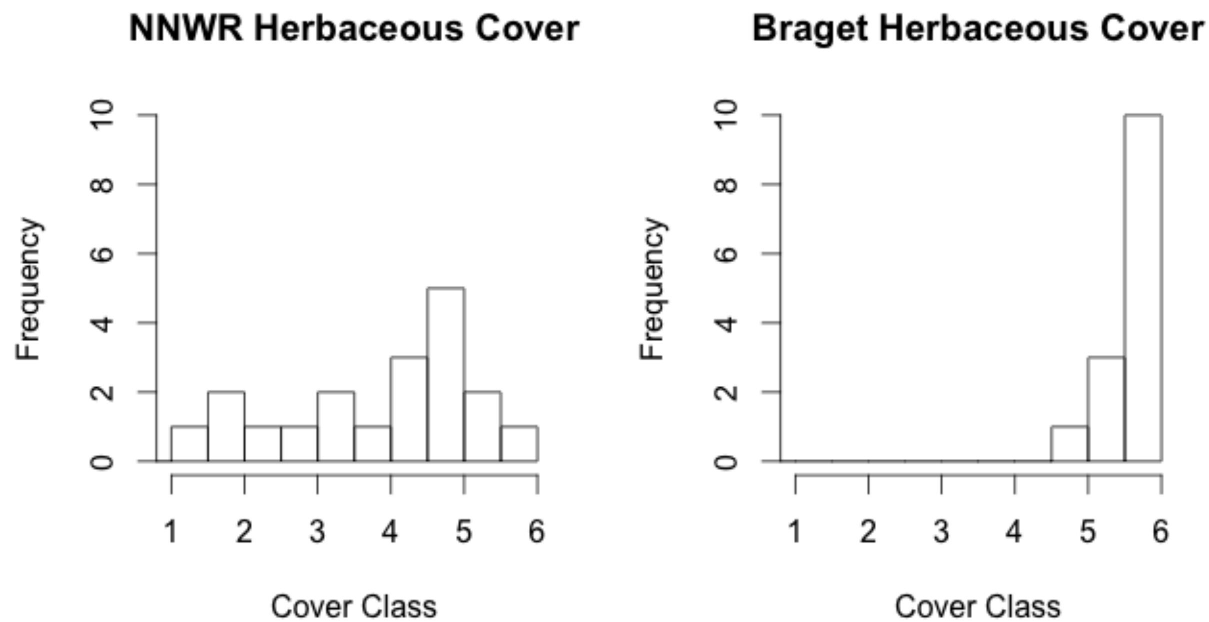

Figure 13: Histograms of herbaceous cover (as averaged between the beginning and end of the growing season) at the two sites. See Table 4 for herbaceous cover class categories.

Plant Response Descriptive Statistics

Between Site Differences

The results of the MRPP show that there was a significant difference between plant responses at the two sites. The NNWR site, on the east side of the river, contained 19 plots, and the Braget site, on the west side of the river, contained 14 plots (Figure 4). Within the NNWR site, there were potentially several distinct areas affecting planting success: the dike footprint and the planting bench area (mulched versus not mulched). However, the sample size within each NNWR planting area was too small for valid statistical comparisons.

Between the two main sites, the chance corrected within-group agreement A-value was 0.122 and the p-value was 0.036. Since the A-value was relatively small (the potential A-value range is -1 to 1, with 0 indicating heterogeneity within groups equal to that expected by chance, and 1 indicating that all items are identical within groups), the NNWR site and the Braget site were broadly overlapping in vegetative response, with a significant difference between the sites. There is a difference in the ranges of both growth and vigor between the two sites. The Braget plots exhibited a greater increase in basal area and a higher average vigor as compared to the NNWR plots.

Plant Assemblages

A total of 620 plants were quantified and 21 installed species were identified on the plots, out of 25 total species planted (see Table 12 in Appendix C). Species that consisted of more than 2% of installed plants measured in the study plots (13+ plants) are included in the following descriptive statistics. These species are clustered rose (*Rosa pisocarpa*), Sitka spruce, Oregon crabapple *(Malus fusca*), Oregon ash, black twinberry, black cottonwood, common snowberry, Scouler's willow (*Salix scouleriana*), Hooker's willow and Sitka willow (*Salix sitchensis*). 48% of all installed plants (278 in total) measured were various species of willow, with willow live stakes that were not identifiable to the species level making up 24% of installed plants (142 in total).

Survivorship

Overall, an average of 51% installed plants per plot survived, with a standard deviation of 26% (Figure 14). At the NNWR site, 45% of installed plants survived since installation. At the Braget site, 59% of installed plants survived since installation. Over the course of the 2011 growing season, an average of 77% of plants survived (only counting plants that were living at the start of the 2011 season). The NNWR site averaged a 66% seasonal survival rate and the Braget site averaged a 93% seasonal survival rate. There was a wide range in survivorship both within and between the sites. Notably, two plots at the NNWR site had an overall survival rate of 0%.

The species that established at the highest survival rate across the study site was the Oregon crabapple, at 80% overall survival (Figure 15). The individual willows that could be identified to the species level appear to have mostly survived, but unidentified willows had a low survival rate, likely bringing the willow species' survival rates down to below 50%. Assuming that the dead unidentified willows are an equal mix of the species, then Hooker's willow was the most successful willow species to establish. Black cottonwood had a 27% survival rate, far below the other commonly installed species.

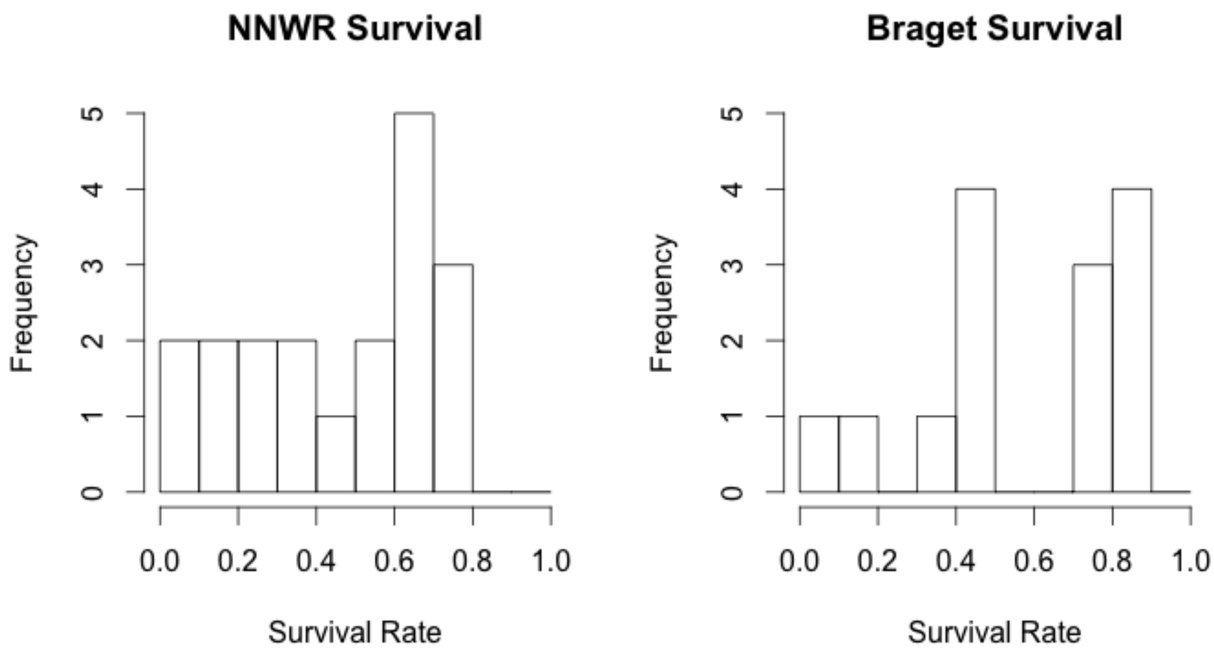

Figure 14: Histograms of plant survivorship at the two study sites, as a proportion of total plants installed (ranging from zero to one).

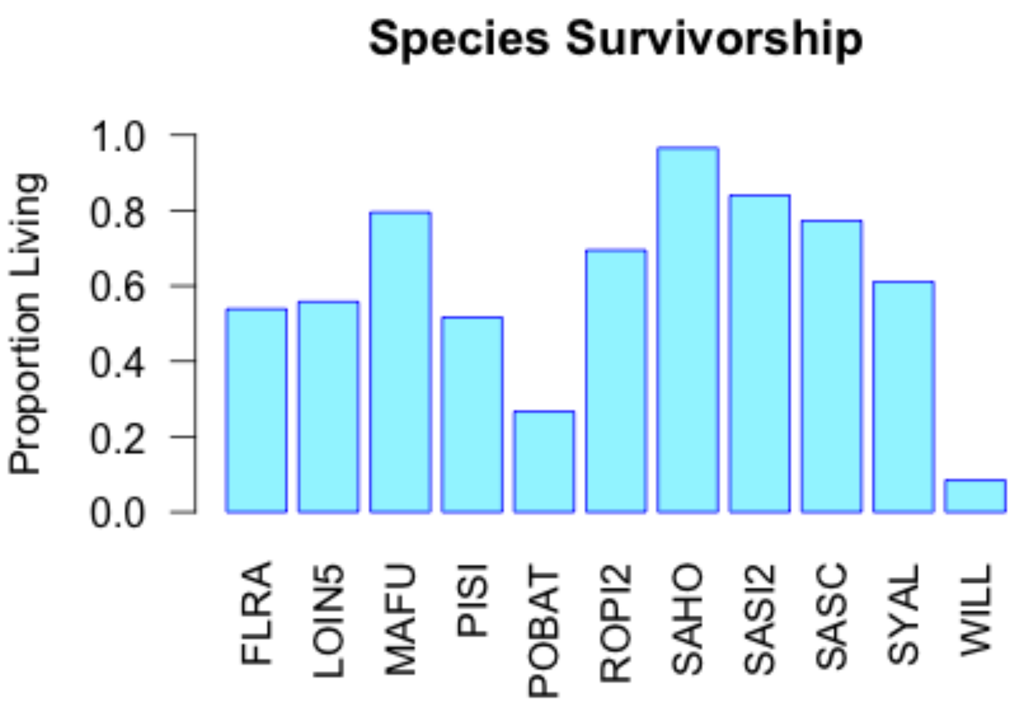

Figure 15: Bar graph of proportion survival of each of the top occurring species (species accounting for 2% or more of total plants measured) and willows not identified to the species level. See Table 12 for species codes.

Initial Basal Area

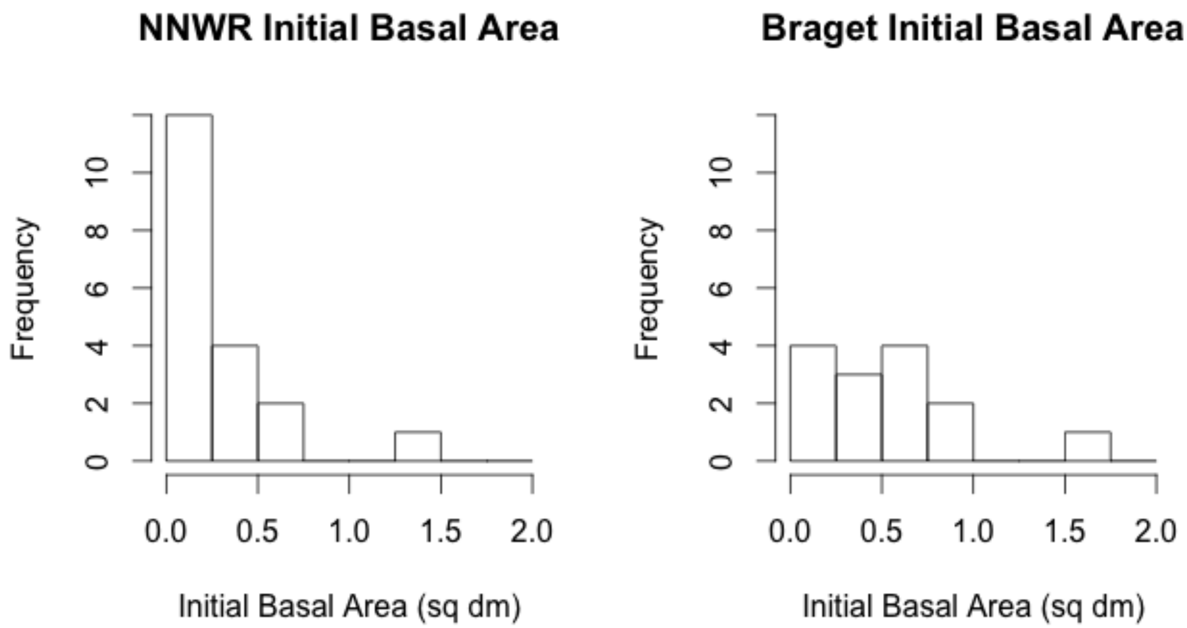

Figure 16: Histograms of initial basal area (in square decimeters) at the two study sites.

The initial basal area coverage of the plots was measured in April 2011, at the beginning of the growing season. There was a 71% positive correlation between initial basal area and survivorship. Overall, the average initial basal area was low, due to the young age of the plants, and extremely positively-skewed in distribution (Figure 16). The age of plants may also account for the large difference in initial basal area between the two sites. The NNWR plots averaged an initial basal area of 0.26 square decimeters. The Braget plots averaged an initial basal area of 0.52 square decimeters, with installed plants that are both a year older than the NNWR plants and double the basal area. See Appendix F for plot level summarized plant response data for all four metrics.

Change in Basal Area

There was a 9% average increase in basal area across all plots (Figure 17). The NNWR plots had a negative change in basal area, averaging a 12% decrease. A negative change in basal area indicates that the growth of living plants did not fully counteract mortality during the growing season. In opposition, the Braget plots had a positive change in basal area, averaging a 39% increase.

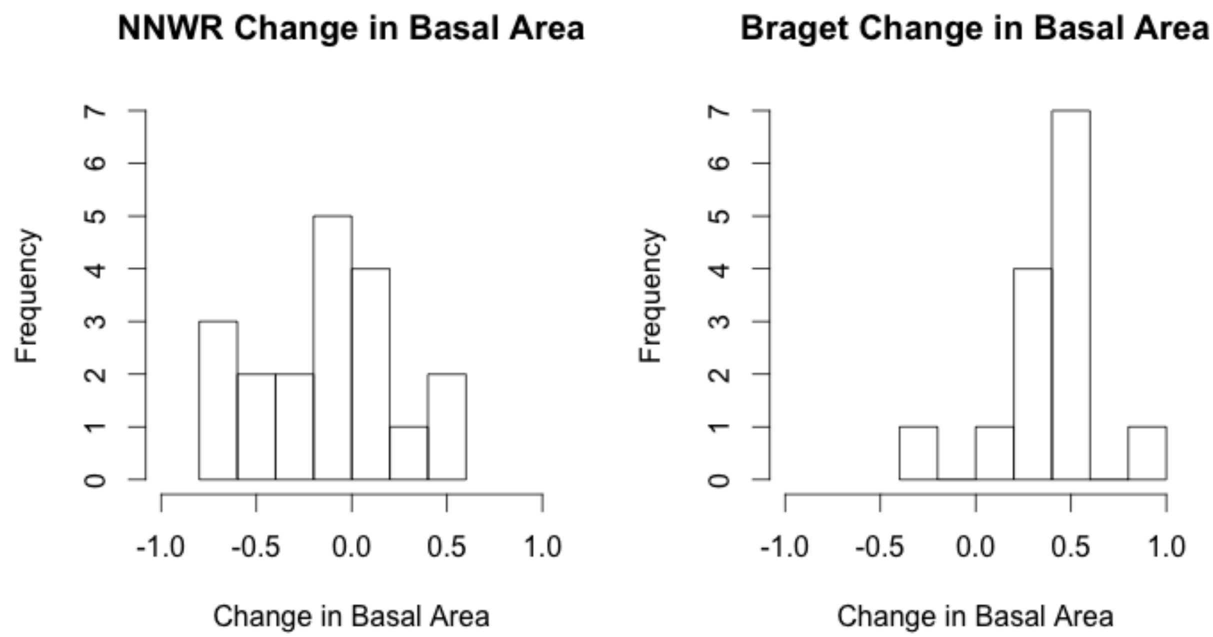

Figure 17: Histograms of change in basal area (in proportional growth) at the two study sites. Potential range of change is from -1 to +1.

Plant Vigor

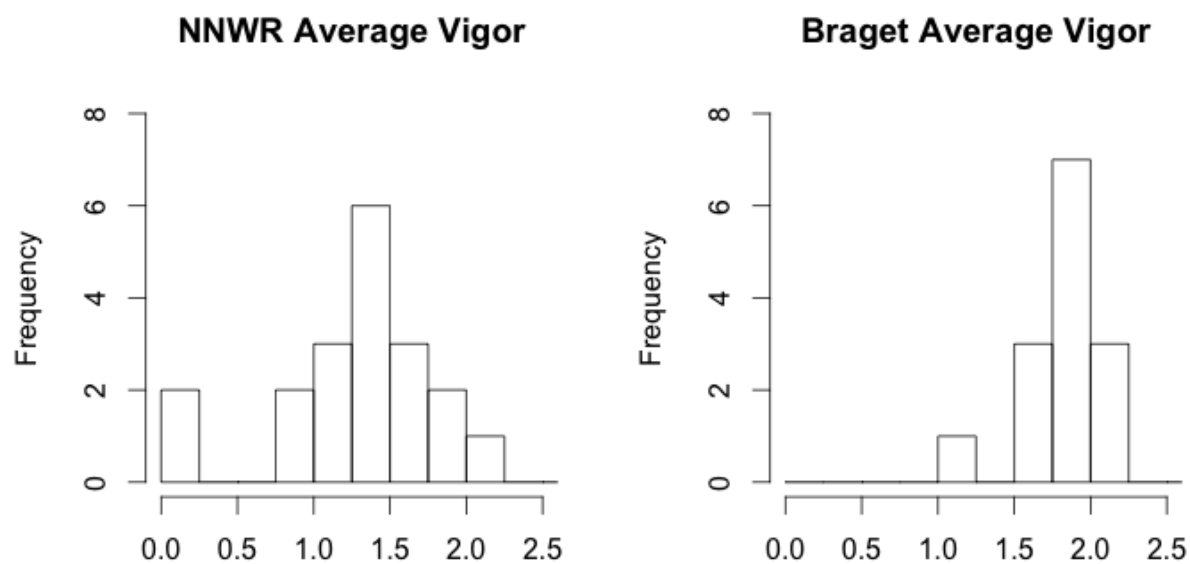

Figure 18: Histograms of vigor (as averaged between beginning and end of growing season) at the two sites. See Table 3 for vigor categories.

Average plant vigor of living, installed plants across both sites was 1.53 (see Table 3 for vigor categories). The NNWR site had overall lower vigor measurements, with a mean of 1.30, as opposed to the Braget site, with an overall average vigor of 1.84 (Figure 18).

Relationships Between Plant Responses and Environmental Factors

Regression Trees

A multivariate regression tree analysis was conducted with all four response variables (survivorship, vigor, initial basal area and change in basal area) and a Manhattan City Block distance measure. The resulting model had a cross-validated error of 1.06. This model has a moderate-to-poor ability to predict group identity, and separated the plots into two groups on the basis of elevation. There were 23 plots grouped at an elevation above 3.33 m above sea level (NAVD88), and 10 plots below that elevation (all 10 plots at NNWR). The higher elevation plots were more successful on all measures.

The survivorship univariate regression tree had a cross validated error of 0.86, indicating that it was moderately successful at predicting the appropriate grouping of new plots. The regression tree split the plots into five groups (Figure 19). The first branch in the tree occurred on the basis of elevation, with 11 plots at elevations above 3.51 m (seven of the 11 plots located at the Braget site) and 22 plots at elevations below 3.51 m (NAVD88). The lower elevation plots had a mean survival rate of 40.2%, whereas the higher elevation plots had a mean survival rate of 72.5%. The lower elevation group continued to split, first on the basis of PC1, with three plots in the low PC1 group (the three overall lowest elevation plots, all at NNWR) averaging a survival rate of only 5.6%, and the remaining 19 plots in the high PC1 group averaging a survival rate of 45.7%.

The group of 19 plots split again on the basis of soil texture. Five plots within the group of 19 (three at Braget and two at NNWR) had a combined clay and silt content of less than 29%, and those plots averaged a survival rate of 30.9%. The remaining 14 plots had an average survival rate of 51.0% and a combined clay and silt content of more than 29%. The group of 14 plots split one final time, on the basis of soil organic matter content, into two equal groups of seven plots each. Plots with soil organic matter content above 8.5% had an average survival rate of 66.2% and plots with soil organic matter content below 8.5% had an average survival rate of 39.5%.

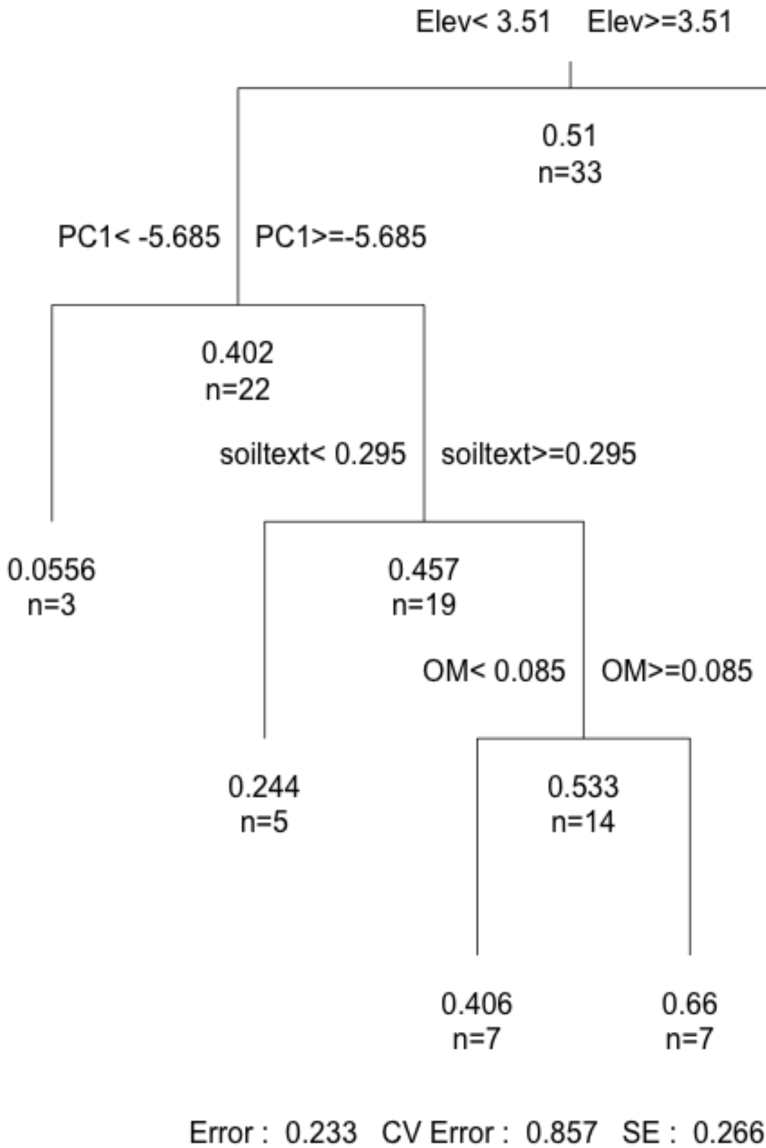

Figure 19: Univariate regression tree for installed plant survivorship. Branches higher in the tree (such as the branching on elevation) indicate more important relationships. Elevations shown in NAVD88.

The vigor regression tree had a cross validated error of 0.45, indicating that it was successfully able to predict group membership for an unclassified plot, on the basis of vigor measurements. The regression tree splits the plots into five groups (Figure 20). The first branch in the tree occurs on the basis of PC1, with 2 plots at NNWR in the low PC1 group and 31 plots in the high PC1 group. This PC1 value is representative of the time series data, and in the original data, the group of 2 plots had an average salinity of 13.38 ppt and an average maximum salinity of 20 ppt, with an average vigor of 0 (vigor was 0 due to the fact that no plants had survived in the plot). The group of 31 plots had an average salinity of 2.58 ppt and an average maximum salinity of 6.52 ppt with an average vigor of 1.63.

The higher PC1 group further split on the basis of average herbaceous cover, with 16 plots with herbaceous cover averaging to over 5.25 (including 13 of the 14 Braget plots) and 15 plots with herbaceous cover averaging to below 5.25 (see Tables 3 and 4 for herbaceous cover and vigor ordinal categories). The average vigor of the high herbaceous cover plots was 1.82 and the average vigor of the low herbaceous cover plots was 1.43.

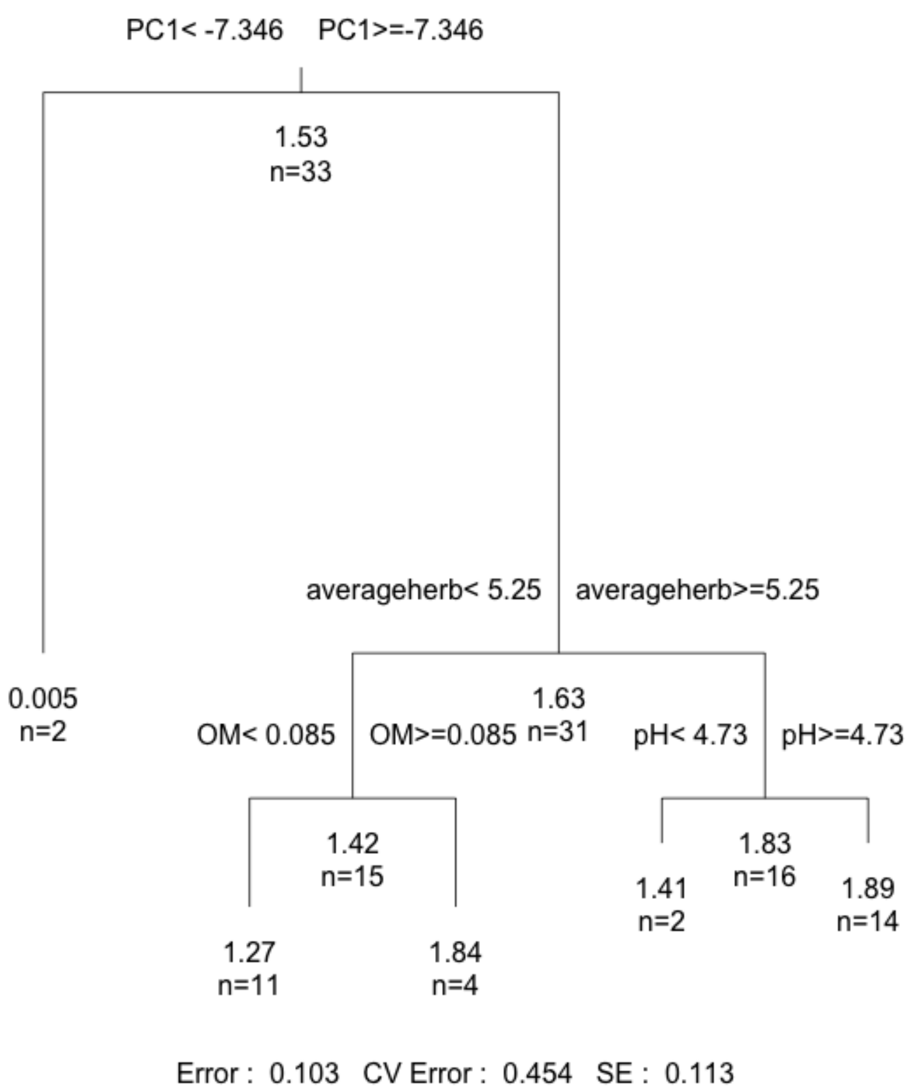

Figure 20: Univariate regression tree for installed plant vigor.

Both of the two herbaceous cover groupings split one final time. The high herbaceous cover group split on the basis of pH. Two plots had a pH below 4.73 (average vigor is 1.41, and both plots located in the northern bench planting area of the NNWR) and 14 plots with a pH above 4.73 (average vigor is 1.89). The low herbaceous cover group split on the basis of soil organic matter content, with four plots of organic matter content above 8.5% (average vigor of 1.84 and all plots in the NNWR, two on dike footprint), and 11 plots with organic matter content below 8.5% (average vigor of 1.29 and all plots at NNWR).

The change in basal area regression tree had a cross validated error of 0.895, indicating that it was moderately successful at predicting group membership for an unclassified plot based on change in basal area (tree not shown). The regression tree split the plots into two branches based on site. The NNWR site had a mean basal area decrease of 12%, and the Braget site had a mean increase in basal area of 39%.

The initial basal area regression tree had a high cross validated error (2.14), indicating that it was not able to predict group membership. The environmental variables collected were not adequately related to initial basal area. The regression tree contained two branches delineated on the basis of PC1 (not shown due to poor prediction ability).

Plot Groupings from Cluster Analysis

A cluster analysis on standardized response data resulted in a dendrogram with low chaining (Figure 21). The dendrogram was separated into five groups based on a scree plot of fusion distances versus number of groups. Slope drastically decreased after five groups, indicating that it was an apt stopping point. Approximately 66% of information was accounted for with five groups.

	Survivorship	**Initial BA (sq. dm)**	**Change in BA**	**Vigor**
Group 1	72%	0.37	0%	1.80
Group 2	80%	0.97	47%	1.92
Group 3	31%	0.18	36%	1.32
Group 4	0%	0.00	0%	0.00
Group 5	38%	0.18	-59%	1.32

Table 5: Plant groups as determined by the cluster analysis, with mean values. BA stands for basal area.

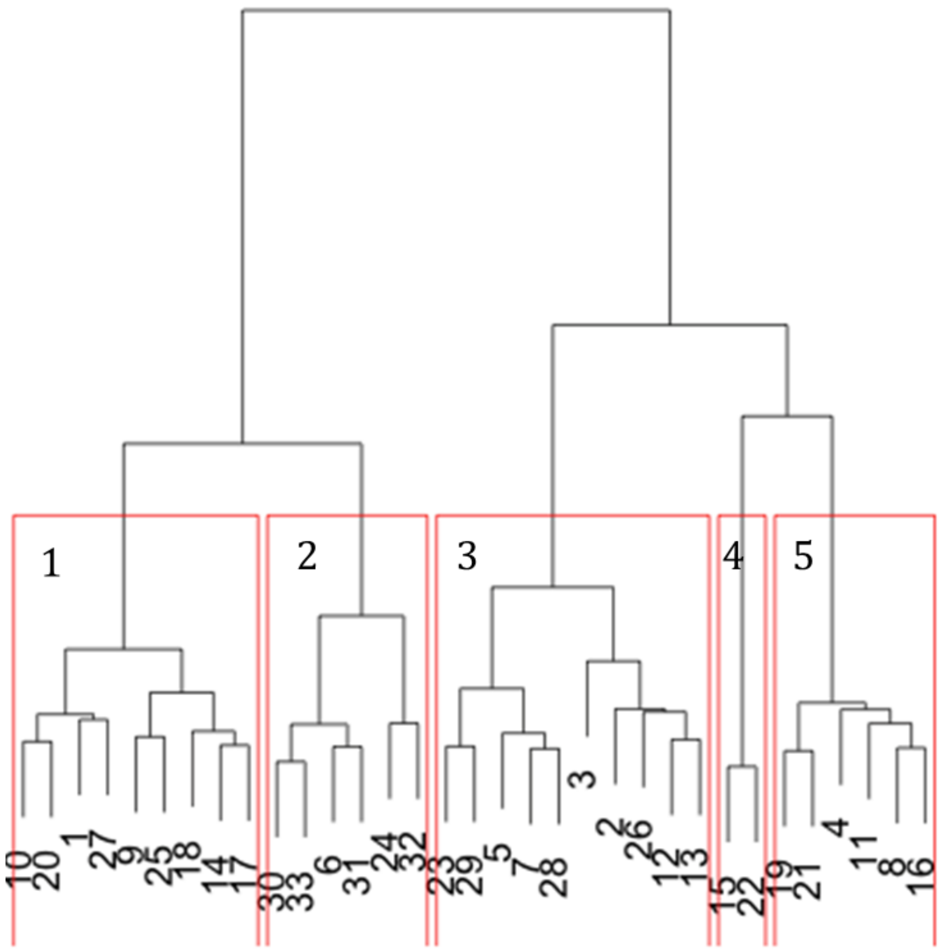

Figure 21: Agglomerative cluster analysis of 33 plots using plant response data, separated into five groups, and leaving approximately 33% of the information remaining. The group numbers correlate with Table 5.

Group 1 consisted of nine plots, seven of which are located at the NNWR site. These plots had a high survivorship rate, a medium initial basal area, no change in basal area and a high vigor (Table 5). This indicates that the surviving plants had a high vigor and most likely put on growth; however there were also plants in these plots that died, and counteracted any positive change in basal area.

Group 2 consisted of six plots with high survivorship, very high initial basal area, substantial growth rate and a relatively high vigor. In other words, this group consisted of the most successful plantings. Five of the six plots were located at the Braget site.

Species	Low Success Groups	# Plants Installed	% Survived	High Success Groups	# Plants Installed	% Survived
big-leaf maple	3	2	0%	2	1	0%
redosier dogwood	3	1	100%	1, 2	5	80%
Oregon ash	3-5	18	17%	1, 2	22	82%
black twinberry	3-5	25	52%	1, 2	15	61%
Oregon crabapple	3, 5	13	92%	1, 2	28	79%
ninebark	3, 5	8	88%	1, 2	6	33%
black cottonwood	3, 5	10	0%	1, 2	5	80%
clustered rose	3-5	19	58%	1, 2	18	78%
Hooker's willow	3, 5	8	100%	1, 2	25	96%
Pacific willow	3, 5	6	67%	1, 2	3	100%
red elderberry	3	2	0%	1, 2	3	67%
Scouler's willow	3, 5	16	69%	1, 2	5	100%
Sitka willow	3	18	61%	1, 2	55	87%
Sitka spruce	3, 5	8	13%	1, 2	21	62%
snowberry	3, 5	8	13%	1, 2	10	100%
Western redcedar	3	4	0%	1, 2	9	50%
red alder	-	0	-	1, 2	11	64%
indian plum	-	0	-	2	3	100%
unknown willow	3, 5	113	7%	1, 2	29	24%

Table 6: Summation of survivorship results for species planted into all cluster analysis groups, separated out by low success and high success. Survivorship data for individual species of willow should be viewed with skepticism, as there were a high percentage of unidentifiable willows that died.

Group 3 consisted of 10 plots evenly mixed between the two sites. These plots had low survivorship, low initial basal area, low vigor, and a positive growth rate. This indicates that while there was high mortality prior to the growing season, the remaining live plants put on growth. The species of plants that were installed into these plots to the highest success were Hooker's willow (100% survival), Oregon crabapple (91% survival), Scouler's willow (62% survival), and ninebark (*Lonicera involucrata*) (83% survival and only installed at Braget). These plots had a large percentage of willows (52%) that died immediately after installation and were not able to be identified to the species level. The other willow species that were installed into these plots had mixed survival rates (Table 6). Big-leaf maple, black cottonwood, red elderberry, common snowberry and western redcedar all had a 0% survival rate within this group. Group 4 consisted of two plots at the

NNWR site with 0% survivorship. The willow, clustered rose, black twinberry and Oregon ash plants installed into these plots did not successfully establish.

Group 5 consisted of six plots with a low survivorship, a low initial basal area and a strongly negative change in basal area and a low vigor. Five of the six plots were located at NNWR. The negative change in basal area indicates that these plots had a high in-season mortality rate. The species of plants that were installed into these plots to the highest survival success were Sitka willow (62% survival), clustered rose (69% survival) and black twinberry (60% survival). However, just as in group 3, there were a large percentage of willows (72%) within these plots that could not be identified due to death immediately after installation. If some of those willows were Sitka willows, it would bring down the survival rate of that species. Oregon crabapple and ninebark were planted in very small numbers within these plots (2 each) but had a survival rate of 100%. Black cottonwood, Pacific willow and western redcedar had a 0% survival rate within this group.

NMDS Ordination

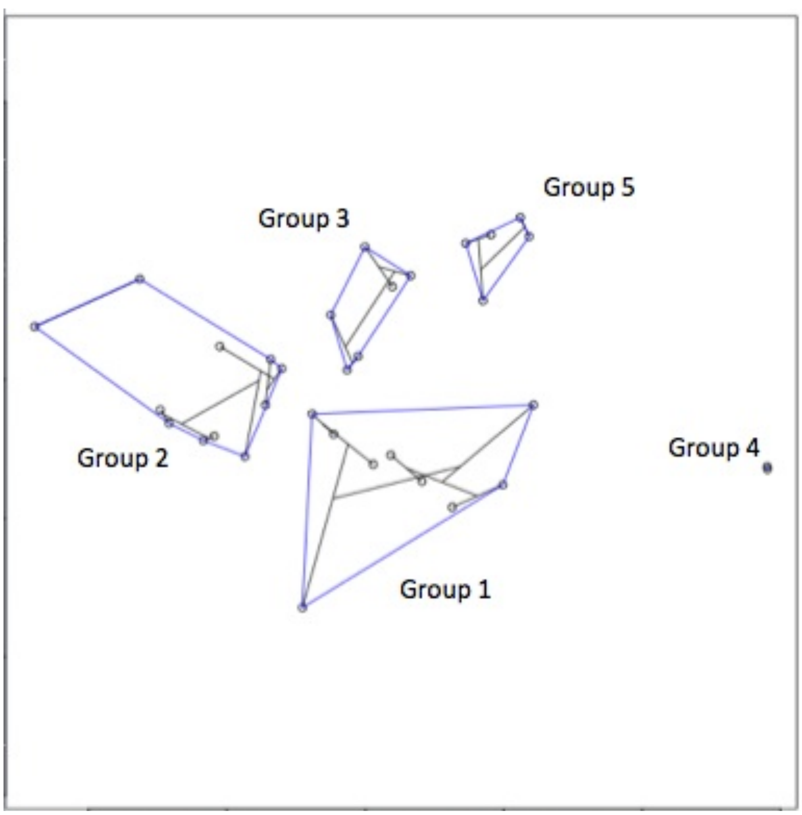

Figure 22: NMDS ordination of plant data with five groups selected. Note that "Group 4" has two plots with zero distance from each other.

A 2-dimensional solution was used in the NMDS ordination, since the stress levels were low. The final NMDS resulted in a stress of 0.05, which indicates that it was "a good ordination with no real risk of drawing false inferences" (Clark, 1993). It took only one iteration to reach the final solution (Figure 22). Group 4 was located furthest away from the other groups, indicating that it was the most different in response variables from the other plots.

Significance of Model

Using an ANOVA to test the overall significance of the dbRDA, we found that the model is significant, at 0.05 with a pseudo-F value of 3.26. Using 500 permutations, the first two axes of the dbRDA are significant at 0.05. CAP1 had a pseudo-F value of 28.67 and CAP2 had a pseudo-F value of 9.13.

At 99 permutations each, and at an alpha level of 0.05, an ANOVA test found that site (0.01), elevation (0.01), PC1 (0.01), soil bulk density (0.01), soil organic matter (0.05) and the interaction between soil organic matter and herbaceous cover (0.02) were significant variables . This means that these variables are all related to the success rate of the restoration plantings (Figure 23). The most successful plots were located on the Braget site, in areas with high elevations, high PC1 values (positively correlated to depth to water and negatively correlated to salinity and soil moisture) and both high herbaceous cover and high soil organic matter. Site had a pseudo-F value of 13.37 and explained 19% of total variation. PC1 had a pseudo-F value of 6.87 and explained 10% of total variation. Elevation had a pseudo-F value of 5.59 and explained 8% of total variation. Soil bulk density had a pseudo-F value of 4.47 and explained 6% of total variation. Soil organic matter had a pseudo-F value of 3.25 and explained 5% of total variation. The organic matter/ herbaceous cover interaction term had a pseudo-F value of 1.68 and explained 8% of total variation. In total, at an alpha level of 0.05, this model explained 56% of total variation in multivariate planting success.

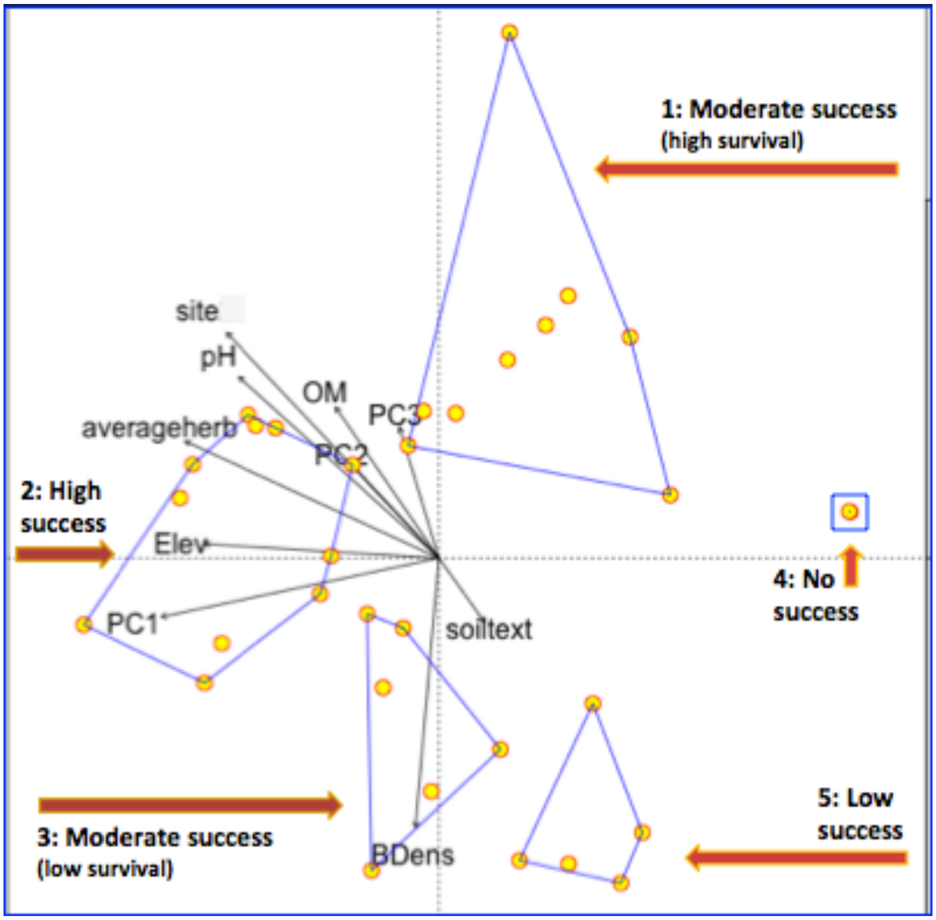

Figure 23: dbRDA of response variables overlaid with environmental variables. Site, elevation, PC1 soil bulk density, soil organic matter and the interaction of organic matter and herbaceous cover are all significant variables (0.05) relating to the success of the plantings. The sites are arranged into five groups as determined by the cluster analysis.

PC2 was additionally significant at the 0.10 alpha level (0.09) at 99 permutations and was positively correlated with soil moisture (with a moderate negative correlation to both soil salinity and depth to water table). It had a pseudo-F value of 2.70 and explained 4% of total variation. At the 0.10 alpha level, the model explained a total of 60% of variation in planting success. Other factors (not included in this dataset), which are examined in the discussion, may have influenced planting success and could have explained some the variation not contained within this model.

Discussion

The goal of this analysis was to determine the relationships between restored tidal processes and the environmental boundary for establishment of native woody plants in freshwater tidal swamps. The first step in determining these relationships was to quantify both the establishment of native woody vegetation and the environmental processes. Planting vegetation can increase the speed at which preferred species establish at a restoration site (Diefenderfer, et al., 2008), but only if installed in appropriate conditions to support growth. By sampling the plantings in the lowest elevation areas, we were able to identify threshold conditions for viable woody plant development.

Planting Success

The effectiveness of native plantings can be determined by measuring survival, health, and growth of the plants over time. In this study, sites were chosen within areas that were expected to the most stressful for woody plant establishment, along with areas that were expected to be less stressful. Not surprisingly, there was wide variation in the success rate of these restoration plantings, by all measures. With the stressful conditions present in tidal swamp restoration sites, it is to be expected that growth, vigor and survival would be depressed lower than in a non-tidal forested wetlands restoration site.

In order to grow, a plant must survive, and with its speed of use, survivorship assessments are a primary monitoring technique utilized to determine woody plant restoration success. The Washington State Department of Transportation considers a 75% or higher survival rate at three years after planting indicative of a successful project (2008). Even though three years has not yet passed since the Nisqually restoration plantings, the 51% survival rate is far below the 75% cutoff. For a few different reasons, this metric of success is not valid here. First, the low survival rate in marginal areas was expected, as one of the planting goals was to establish some woody vegetation within ecological transition zones, creating patchy edge habitat similar to natural systems (Barham, pers. comm.). Also, with so little currently known about the restoration of Pacific ecoregion tidal swamps, it is not clear what an appropriate survival rate metric would be.

Of the plants that did survive, growth rates over the 2011 growing season were very low. This is unlikely related to stressful climate conditions, which usually consist of hot and droughty summers (NOAA, 2004). In fact, the summer of 2011 was atypically cool. May through July was the coolest such period on record (since 1895) in western Washington (NOAA, 2011b). August and September did warm to normal summer temperatures. Low growth rates were most likely a function of both stressful conditions and the fact that young and newly installed seedlings do not generally put on ample growth until the third summer after installation (Gilman, 1997).

Planting Success by Species

A main challenge in interpreting the planting success of individual species was the predominance of willows installed into the site and the high rate at which they could not be identified. Approximately ½ of all plants installed in the monitoring plots were willows, and approximately ½ of the willows (¼ of all plants) died immediately after installation as live stakes. This made it virtually impossible to distinguish the species of the dead willow stakes. Without that knowledge, we were not able to determine the overall survival rates of the different willow species. Additional research is necessary in order to define which species of willows have the highest success rate in the varying conditions present in tidal swamp restoration sites. All four species of installed willow had high seasonal survival rates.

In the low success cluster analysis groups, Oregon crabapple, black twinberry and clustered rose were installed in substantial numbers to relative survival success. Oregon crabapple specifically stood out for surviving at high rates (80%) in the lowest elevation plots (below 3.5 m, NAVD88). Black cottonwood and Western redcedar had notoriously low survival rates, both in the low success groups and in the higher success groups. The majority of other species installed were not recorded in high enough numbers to allow for interpretation of survival rates between sites or between cluster analysis groups.

Environmental Conditions

A tidal freshwater forested ecosystem can be defined as a low-lying, tree dominated wetland with hydric soils, adjacent to the upper reach of an estuary, that is periodically inundated by low salinity water (<0.5 ppt) and is tidally influenced by tidal exchange and river flow (Mitsch & Gosselink, 2007). The areas examined in this study are low-lying, contain hydric soils and are adjacent to the upper reach of the Nisqually Estuary. The goal of the restoration plantings was to propel the sites' trajectories towards a tree and/or shrub-dominated ecosystem. This leaves the following factors: periodic inundation by low salinity water, and tidal influence by tidal exchange and river flow. Accounting for herbivory and time since installation, and assuming both that appropriate plants were selected and that plants were installed properly, then the data suggest that some of the measured salinities and hydrologic site conditions do not support the rapid establishment of a tidal freshwater swamp. This is not unexpected, as land managers purposefully overplanted into marginal areas to allow natural delineation of swamp habitat. Also, this study and other recent research indicate that the establishment of Pacific ecoregion tidal swamps is possible in some sites with brackish salinities (Brophy, 2009).

Interpretation of the Grouping Analyses and the Multivariate Model

In assessing the relationship between environmental conditions and woody plant establishment, it was found that site, elevation, PC1, PC2, bulk density, organic matter and the interaction of organic matter and herbaceous cover were significantly correlated with multivariate planting success and explained 60% of total planting success variation (0.10 alpha level). Other factors that would explain additional variation in planting success and are currently missing from the model are explored further in the "Other Factors Affecting Planting Success" section (page 64).

Planting Success and Site

It is not surprising that the two sites are significantly different from one another in planting success. Past land use was very different between the two sites. The Braget site was maintained as a pasture for cattle for many decades prior to restoration, whereas the

NNWR site was maintained as a freshwater wetland for wildlife. The extent of earthwork at the Braget site consisted of some tilling of the invasive grasses, whereas the NNWR site saw extensive earthwork in the form of dike removal. The highly disturbed former dike footprint did not receive any site preparations following dike removal, which most likely impacted both soil organic matter content and soil texture. Even so, the survivorship of species installed on the former dike footprint did not differ significantly from the survivorship of species installed in other areas of the NNWR (47% on former dike footprint versus 44% elsewhere). See the "Restoration" section, starting on page 11, for additional information on differences between the two sites.

Geographically, the locations of the two study sites are offset along both the north/south and the east/west plane (Figure 4). The Braget site consisted of higher elevation plots, lower soil salinities and deeper water tables. These factors all correlate with planting success. Additionally, the study was conducted 2.5 years after install of the Braget plantings and 1.5 years after install of the NNWR plantings. The NNWR plants were most likely still establishing, due to being younger and in the ground for less time.

Young plants have small or underdeveloped root systems and do not put on extensive aboveground growth until they achieve the extensive root development required to sustain them through future drought seasons as they mature. In temperate climates, it takes at least two years for installed seedlings to establish, with substantial growth not occurring until the third growing season (Gilman, 1997). The difference in plant age most likely plays a large role in the notable differences in basal area growth between the two sites. The NNWR plots actually had a negative change in basal area, averaging a 12% decrease, whereas the Braget plots had a positive change in basal area, averaging a 39% increase. The apparent negative growth rate in the NNWR plots is an indication that high mortality rates counteracted any positive (yet low, due to age) growth rates of living plants.

Planting Success and Landscape Position

Elevation was strongly correlated with planting success and co-varied with PC1. Elevations located below a depth of ⅓ m above mean higher high water (MHHW) did not support woody plant growth. Specifically, cluster analysis groups 3, 4, and 5, which contained 17 low success plots (Table 5), were planted at an average elevation of 3.31 m above sea level (NAVD88). This elevation corresponds to 0.29 m above MHHW. These plantings had only a 30% survival rate since planting, and put on an average of 0% growth in basal area. Plots located close in elevation to MHHW were inundated frequently and consistently. In contrast, cluster analysis groups 1 and 2 (Table 5) contained 16 plots with a higher planting success rate. These plots were located at an average elevation of 3.53 m above sea level (NAVD88), or 0.51 m above MHHW. These plantings had an average survival rate of 73% and grew 19% in basal area in 2011. A difference of only 0.22 m in elevation between these two groupings corresponds to a major difference in planting success. However, antidotal evidence suggests that woody vegetation can establish at lower elevations, in freshwater regimes. Willows have been found growing as low as 2.5 m above sea level (NAVD88) right along the edge of the Nisqually River (Barham, pers. comm.), which is ¼ m lower than the lowest plot measured in this study.

Lower elevation sites corresponded to wetter sites (the correlation between elevation and PC1 was 65%). In wetter sites, seedlings are at an increased risk of flooding related mortality as compared to established trees (Glenz, et al., 2006). Qualitative observations on site indicated that most sites were tidally influenced by ground water and some of the lower sites also received periodic tidal surface water inundation.

The lack of microtopography evident on site (via qualitative field observations and LIDAR imagery) is indicative of a missing key piece in the re-creation of the ecosystem. Now that natural hydrology has been restored to the system, future significant flood events may create microtopography via fluvial processes and the importation of large wood. Microtopographic variation in floodplain systems is often caused by buried large wood (Collins et al., 2012). In Pacific Northwest floodplains, dominant Sitka spruce, Douglas-fir (*Pseudotsuga menziesii*) and Western redcedar (*Thuja plicata*) form stable alluvial patches (Fetherston, 2005). It is only upon these hard points that conifer trees can grow with the necessary physical stability for the required 100 – 200 years to reach maturity. Once trees reach maturity and fall, they create topographic features and hard points in the floodplain, continuing the positive feedback cycle and ensuring the growth of future large wood (Fetherston, 2005).

In addition, some conifer species reproduce preferentially on wood, regardless of hydrology (Franklin & Dyrness, 1973). Fetherston found that 99% of Sitka spruce seedlings regenerated on fluvially organized large wood in an Olympic Peninsula river floodplain (2005). For conifers, large wood pieces in the estuarine floodplain could serve as a seedling nursery. In the Nisqually River valley, the selective logging of conifers in the late 19th century greatly reduced the occurrence of Sitka spruce and Douglas-fir in the watershed (Collins & Montgomery, 2002). However to counteract this lack of large wood in the watershed, at the NNWR restoration site, land managers incorporated large wood into numerous small log jams through the planting area. Some large logs were removed in the process of clearing the dike for removal, and they were spread across the dike footprint prior to planting in areas adjacent to existing forested areas.

The low occurrence of large conifers was evident both in the Nisqually restoration sites and in the reference site. This may indicate that the reference site was not functioning at its climax successional state due to human induced disturbances. Instead, with the lack of large wood, the reference site could be trapped as a mid-seral deciduous tree/shrub system, unable to develop into a Sitka spruce tidal forested climax ecosystem. On the other hand, in this historically dynamic system, disturbance regimes can be very important, and early successional habitats may be the norm for the Nisqually floodplain tidal forest systems. Furthermore, many species rely on both disturbance and early successional habitats (Townsend, et al., 1997). Even if it is impossible to determine the historical community composition in the Nisqually tidal freshwater swamp reference and restoration sites, restoring to a Sitka spruce dominated tidal swamp would be an appropriate goal. The Puget Sound region would benefit from the added ecological functions and diversity of habitats created in by restoring this increasingly rare ecosystem type (Dale, et al. 2000).

Planting Success and PCs

An interpretation of the PCA is necessary in order to understand the ecological significance behind PC1's positive correlation with planting success. PC1 was also positively correlated with depth to water, indicating that the higher PC1 values corresponded to deeper water tables. PC1 and depth to water table were negatively correlated to salinity, with higher water tables relating to increased pore water soil salinity.

This indicates that the summer water table was influenced by tidal influxes, which may be predominantly brackish or predominantly freshwater, depending on complex hydrologic interactions. Plantings were less successful at low values of PC1.

The opposing correlations between soil salinity and depth to water table/soil moisture in PC1 and PC2 indicate that the relationships between soil salinity and the hydrologic variables are not linear. Some plots have predominant influxes of freshwater (which would lead to a negative correlation between a rising depth to water table and soil salinity), whereas other plots have a predominant influx of brackish water (leading to a positive relationship between a rising water table and soil salinity). PC1 accounts for the negative correlation between deep water tables and high soil salinity.

PC2, which was a significant predictor of planting success at the alpha 0.10 level, was positively correlated with soil moisture, and had a moderate negative correlation with both soil salinity and depth to water table. This indicates that PC2 was the explanatory variable most related to soil moisture. As soil moisture increased, soil salinity and water table depth decreased. Since soil salinity and depth to water table co-varied in PC2, PC2 likely accounted for the variation resulting from plots with a high influx of fresh water found at both the Braget site and the NNWR site.

In the plots where the hydrologic influx was more saline, a deeper water table indicated higher planting success. In these cases, the deeper water table meant that the saline tidal waters were not within access of the plants (perhaps because the water table was deeper than the root zone). This relationship is statistically significant, indicating that areas of brackish tidal influence during the growing season resulted in decreased planting success. Specifically, many of the plots covered in this study had average and maximum soil salinities that far exceeded both 0.5 ppt (the upper limit for freshwater salinity) and 2.0 ppt (the known upper limit of soil salinity supporting Pacific Northwest native tree growth).

However, data from Brophy (2009) indicate that higher soil salinities can support tidal brackish swamps. In reference swamps in Oregon, Brophy found reference Sitka spruce and black twinberry dominated brackish swamps at average summer soil salinities of 5 - 20 ppt (2009). However, woody plant cover was low to non-existent within the adjacent, recently restored/planted, tidal swamp sites (Brophy, 2009), which begs the question: how can we recreate tidal swamps in areas of elevated salinity?

The plots with low survival rates in this study (cluster analysis groups 3, 4 and 5) had an average soil salinity of 4.3 ppt and an average maximum measured soil salinity of 8.6 ppt. Groups 3 and 5 had installed survival rates of 31% and 38% respectively, which while low, may eventually result in development of a shrub-scrub or forested swamp. Group 4 contained plots that did not support woody plant growth, located in areas of elevation below MHHW with brackish salinities. In contrast, the plots with high survival rates (cluster analysis groups 1 and 2 at 72% and 80% survival respectively) had an average soil salinity of 2.5 and an average maximum measured soil salinity of 5.9. Brophy's research indicates that willows naturally occur in lower salinity sites (2009), and as approximately ½ of the plants measured in this study were willows, it makes intuitive sense that the higher success plots were those with lower salinities.

Planting Success and Soil Variables

Soil organic matter was strongly correlated with planting success, with higher success planting occurring in plots with higher organic matter. Overall, the plots with higher soil organic matter were located at the Braget site. Differences in past land use and restoration site preparation between the two sites most likely played a large role in the dissimilarities in soil organic matter content (see the "Restoration" section starting on page 11 for more information).

In general, the proportion of soil organic matter w higher in undisturbed tidal wetlands (Cornu & Sadro, 2002) and most likely decreased in the Nisqually River delta sites following installation of the dikes a century ago. Even though the tidal dikes have now been removed, an increase in soil organic matter to historic levels may take decades (Frenkel & Morlan, 1991). Soil organic matter is essential for plant establishment and growth as it facilitates the development of soil aggregates, which improve soil structure and water infiltration (Chaney & Swift, 1984). Soil organic matter also increases cation exchange, increases root growth and fuels the propagation of soil biota (Allison, 1973).

One potential line of future research into methods of speeding succession towards mature tidal swamps could look into the effects of modifying site soils prior to planting, with a goal of increasing organic matter. Potentially beneficial site preparation activities include the additions of organic wood mulch, compost or top soil (this may already be necessary if site elevations are to be adjusted) and/or seeding the site with native herbaceous vegetation. The fact that the interaction term of herbaceous vegetation and soil organic matter was significant indicates that in these marginal plots, a strong herbaceous understory is an indication of soil fertility, and that a high coverage of herbaceous plants in combination with higher levels of organic matter resulted in more successful installed native plant establishment. These results support the findings of Turner et al., who show that the formation of a plant understory can aid in the development of soil organic matter in tidal wetlands (2000).

Soil bulk density was correlated with planting success, however this relationship was not as clear as the other significant variables in the model. The soil density measurements on all of the plots were within the range that supports plant growth in sandy and silty soils (Brady, 1990). However, there was a general relationship of increased plant survivorship rates in plots with higher soil bulk density. This may be because the soils with lower bulk densities were loose and porous, allowing for the leaching of nutrients and potential dessication of newly installed seedlings (in plots with higher elevations that did not receive regular tidal flooding). However, additional research would be necessary in order to clarify the relation between bulk density and planting success in these tidal swamp planting areas.

Even though pH was not significant in the model, there were surprising low pH values in some of the plots, specifically on the dike footprint in the NNWR. In general, the majority of nutrients are less available for plant uptake under strongly acidic conditions of less than pH 4.5 (Zwart, 2006). Especially in clay soils, the amounts of exchangeable aluminum at pH levels under 5.5 can be toxic to plants (Sposito, 1989). However, soil pH values are often more acidic under diked conditions, and it is expected that over time, as the NNWR site is exposed to salts in brackish waters, it will buffer the soil pH closer to neutral conditions (Ewing, pers. comm. and Omar, 1994).

Regression Tree Interpretation

The response variables included in the regression tree data analysis were very different types of data from one another. In some ways, this was a benefit, as it is ideal to wholly account for as much variation in planting success as possible. However, survivorship, vigor, initial basal area and change in basal area most likely were correlated to different environmental factors, which would make the multivariate regression tree analysis an uninformative analytical method for this dataset.

The multivariate regression tree did separate out on the basis of elevation above sea level. As expected, the cross-validated error was high, but these results confirmed the results of the dbRDA model, which found elevation to be a significant correlating factor with planting success. Due to high error, the multivariate regression tree was a poor model for determining proper group membership. This indicated that if the response variables did not co-vary, then univariate regression tree models for all four of the response variables would result in differing splits, and lower cross validated errors.

The univariate survivorship regression tree had a medium cross validated error, and split initially on elevation, at a higher elevation (by 0.2 m) than in the multivariate regression tree. This shows that there was no specific threshold value at which elevation was too low, instead that as elevation trended down towards MHHW, the success rate of the plantings decreased as well. The next split on this tree was on the basis of PC1. These first two splits in the tree reinforce the dbRDA results indicating that elevation and PC1 were significant explanatory variables.

The univariate regression tree for plant vigor had a low cross validated error rate, indicating that it was an appropriate model for vigor. The initial split on PC1 indicates that plant vigor was strongly dependent on salinity and depth to water table. The next split in this tree was on the basis of herbaceous cover. The higher vigor plants were in plots with increased herbaceous cover. This suggests that the herbaceous layer was not acting as a competitive force, but instead was an indicator of a fertile site. However, herbaceous cover by itself was not statistically significant in the dbRDA statistical test. The next two splits in the tree support the idea that high herbaceous cover points to greater soil fertility. They split on the basis of soil pH and organic matter, with higher vigor plants in plots with higher (closer to neutral) pH and in plots with higher proportions of organic matter. Soil organic matter was significant at the alpha 0.05 level in the dbRDA statistical test.

The regression tree for change in basal area had a high cross validated error rate, indicating that it was not a suitable method for group selection. This most likely has to do with the fact that this response variable was mostly dependent on initial plant install choice. Different plots had different suites of species installed on them, as designated by land managers. At the NNWR site, planting areas were designated as "brackish" on the dike footprint, the "southern bench (drier areas)", the "southern bench (wetter areas)' and "northern bench". The dike footprint and northern bench areas were included in this study and had different mixes of species installed in them. Not only do different species have a variety of growth rates, but some species started out with a substantially higher basal area than others. For example, all *Salix* spp. (willow) propagules were installed in the form of a live stake. These live stakes were up to 6 cm in diameter, which was an order of magnitude higher than the diameters of other installed plants, such as the Western redcedars.

The regression tree for initial basal area had a lower cross validated error, showing that the regression tree was moderately successful at group selection – however the groups were split solely on the basis of site. With the trees in two different stages of growth (second summer after install versus third summer after install), it is no surprise that the older, more established trees were able to put on increased aboveground growth prior to the start of the study. This regression tree did not add any ecological insights.

Overall, regression tree analysis was not a sufficient model by itself for predicting planting success response. However, this model did support the drRDA statistical model, and yielded nuanced insights into the potential relationships within plant response variables and between response and explanatory variables. Future research would be needed to confirm these initial results, which indicate that elevation was the most important factor in plant mortality, whereas live plant vigor had an increasing dependence on soil salinity (in addition to elevation/water table).

Other Factors Affecting Planting Success

Since the plantings had been in the ground for two to three growing seasons, this study was not able to account for the environmental conditions prior to April 2011. The climatic and hydrologic conditions of previous years may have a large effect on seedling success. Hot summers with low precipitation rates are common in the Pacific Northwest and can lead to high seedling mortality rates. In areas of the study site where the water table was lower than the rooting zone, plants may have died or put on minimal growth due to water stress. This study indicates that low river discharge leads to higher soil salinity in the tidal freshwater/brackish riparian zone (Figure 8). If the Nisqually's discharge was even lower in past summers, then the greater ratio of saline water would have killed seedlings in areas of the study site with a high water table.

Another confounding factor affecting the survival, growth and vigor of the plantings was herbivory. Specifically, we observed evidence of extensive herbivory by black-tailed deer on the commonly installed species Western crabapple and Oregon ash. The observed herbivory certainly decreased vigor and height growth, and may have affected mortality.

Additionally, this study did not measure redox potential within the wetland soils due to time and funding limitations. However, many studies indicate that redox potential is a strong predictor of planting success in wetland soils (Ewing et al., 1991; Anastasiou & Brooks, 2003; and Fiedler et al. 2007). When redox potentials fall below certain values, such as -50 mV, a sharp decline in plant health can occur (Anastasiou & Brooks, 2003).

Finally, seedling success can often be traced back to both how the plant was handled prior to planting and to installation technique. Bare root seedlings must be handled with care to decrease stress and root desiccation. Bare root plants that are placed in direct sun, or left with their roots exposed to air prior to planting will rapidly deteriorate. Potted plants that are installed without removal of the potting soil medium often struggle to put on root growth. Additionally, poorly installed seedlings of both the bare root and potted varieties are prone to increased mortality and low growth rates (Chalker-Scott, 2009). It is possible that the a portion of the decreased planting success observed in the Nisqually tidal forested wetlands may be due in part to pre-installation handling and planting techniques.

Sources of Error

Because the removal of tidal dikes and installation of restoration plantings were singular large events, there is the possibility of pseudoreplication, where the sampling plots were not independent. If this is the case, then we are statistically limited in our ability to make broad inferences and apply them to other watersheds. However, the ecological insights gained in this observational study are still applicable. Tidal freshwater swamp restoration projects are increasing, and this detailed assessment of the Nisqually tidal floodplain site following restoration may aid in the design of future projects.

Also, multiple years of growth and survivorship data were not taken. The fact that this study was conducted over the course of one growing season may be a cause of error. Climate conditions vary from summer to summer and may have strong impacts on seasonal mortality, vigor and growth. Also, seedlings in their first few years after planting often put on very little growth, regardless of site conditions.

Finally, since plants were not installed inside protector tubes at the NNWR site, the location of installed plants was not always clear. At the beginning of the growing season, plants were recorded when herbaceous vegetation was low to the ground. In October, when plants were re-measured, the herbaceous vegetation had grown taller than many installed plants. A small percentage of plants recorded in April were no longer visible in the plot, and were presumed dead. If they were actually present and alive, this means that we may have overestimated mortality rates slightly in the NNWR plots.

Summary

Management Implications

This study indicates that the collection of baseline data would yield valuable information for the restoration of tidal freshwater swamp habitat. Specifically, we recommend that land managers take repeated measures of growing season soil salinity, in addition to mapping elevation (as related to tidal extent), across the site. The complex interactions between saline marine waters, freshwater, ground water, surface water and elevation makes it difficult to predict in advance where salinities will be too high for woody plant establishment. Depth to water table measurements, while less essential to determine planting areas, would also aid planning efforts (with the added benefit of providing easy access to pore water soil salinity).

If a quality reference site is available, replica baseline data should be collected at the reference site as well. However, it can be challenging to find reference sites, as nearby sites may have changing hydrology and salinity regimes as a result of project actions. Also, in the case of this study, and presumably in other potential reference sites throughout Puget Sound, the majority of reference sites developed to their current state while dikes were in place. The presence of dikes drastically alters hydrologic mixing and inundation patterns within the reference sites. One way to address this issue would be to track changes concurrently at a reference site and at the restoration site in the years following hydrologic restoration (Barham, pers. comm.).

If a tidal swamp restoration project was planned multiple years in advance, reference sites could potentially serve a very different purpose – as a source for locally adapted plant material to grow in preparation for plant installation. In choosing an area to collect propogules (seeds, live stakes and cuttings), project managers should aim for a site with similar soil types, elevations, and salinity regimes to what is expected at the restoration site (Luna & Wilkinson, 2008). Even without substantial lead time, woody species that root from live stakes can be sustainably harvested from reference sites. Whereas this study cannot make any statements regarding the relative success of installing locally adapted tidal swamp woody plants, it is an intriguing line of potential future research. It is possible that in order to successfully reestablish Pacific Northwest tidal brackish swamps, land managers will have to install plants that are locally adapted to grow under the unique stressful conditions of elevated salinity and pulsed tidal flooding.

There is a balance to be made between time spent monitoring and evaluating the site and moving ahead with plant installation. Most Pacific Northwest woody restoration plantings take place in winter, so it is often possible to immediately install trial plantings in the interim year prior to the main planting effort. In the summer following hydrologic restoration, land managers would be able to observe the results of the trial plantings and to monitor and map the proposed site's elevation, salinity and depth to water in the growing season. A planting plan would be developed that fall, with plants installed in winter. The potential increased information collected over an additional year of site monitoring would probably not be worth the risk of leaving the site unplanted for more than a year. Invasive species could develop dominance in the disturbed environment. Land managers must also take into consideration the fact that there are often logistical considerations and funding timelines preventing the long-term collection of baseline data.

When planting into low areas (½ m above MHHW or lower) or in areas that average salinities above 3 ppt, restoration ecologists should anticipate slower growth and higher mortality rates than in non-tidal freshwater swamp habitats. The reference sites used in the design of this restoration planting plan and in Brophy's report (2009) indicate that the closer to the river (aka the less saline the water), the lower the elevation in which wetland woody plants will survive. Willows along the Nisqually River and in Oregon reference sites have established to an elevation as low as ½ m below MHHW (2.5 m NAVD88) (Brophy, 2009).

This study shows that areas with both low brackish waters (2 – 5 ppt) and low elevations have severely decreased planting success, which should be anticipated if planting into that salinity range. Brophy found that reference brackish tidal swamps in Oregon were dominated by black twinberry and Sitka spruce with brackish summer salinities of 5 - 20 ppt (2009). These brackish swamps were all located at 0.5-0.7 m above MHHW. However, Brophy also found very low woody plant cover two years out, at both of the two restoration sites she studied (2009), which supports the findings in this study of high mortality and low growth rates of installed woody plants under brackish conditions.

Elevation and pore water soil salinity values are relatively easy measurements to take prior to restoration planting in order to guide planting design plans. However, both of those variables can change as time passes after hydrologic restoration. Land may accrete or erode with tidal processes, and as the site stabilizes post hydrologic restoration, freshwater and tidal channels may develop or move. This would create additional microtopography and potentially import LWD (large woody debris) into the system.

In order to aid in the physical development of tidal forested wetlands, the installation of coniferous LWD across the floodplain is recommended. In reference tidal freshwater swamps in the Pacific Northwest, microtopography has been found to be a key factor in tree establishment (Diefenderfer & Montgomery, 2009). The majority of woody plants (mostly red alder at high density) that volunteered within the Nisqually Delta study area did so in areas that were mulched. The unevenly spread mulch may be creating microtopography that confers some of the characteristics of habitats with LWD. Also, a variety of native tree and shrub species were found growing upon large wood pieces placed on the dike footprint at the NNWR site. The vigor and size of these plants surpasses those that were installed, and suggests that they established from rhizomes and root materials that were attached to the large wood prior to being moved in the construction process (data not shown).

Installation of LWD may dramatically speed the successional process by creating microtopography and allowing the establishment of conifers. Future research on the relationship between installed plant establishment and human installed microtopographic landscape variation (LWD) within these restored sites may help to illuminate the ideal conditions (including hydrology and disturbance regimes) for directing ecosystem seral development into a climax community tidal freshwater swamp.

Conclusion

One of the main goals motivating the Nisqually Delta restoration project was to "conserve, manage, restore, and enhance native habitats and associated plant and wildlife species representative of the Puget Sound lowlands, with a special emphasis on migratory birds and salmonids" (NNWR, 2005). Within the riparian zone, the overarching objective is to "provide for the protection, restoration, maintenance, and enhancement of the ecological functions … of riparian mature mixed forest habitat in the Nisqually River delta and corridor to provide foraging and breeding habitat for migratory and resident landbirds" The restoration of ecosystem processes that will create tidal freshwater forested habitat and associated functions within the estuary is a vital step towards achieving these goals. Even though seedling survival rates in this study were lower than ideal, data was collected from sites that represented limits on the establishment of woody plants. The installed restoration seedlings will continue to grow where they are supported by proper environmental conditions and recruitment will occur from nearby reference sites. With the floodplain and river reconnected, and as the system develops structural diversity, it will likely lead to increased habitat for migratory passerine songbirds and increased production of prey for young out-migrating salmon (Garono, et al., 2006).

Tidal freshwater forested wetlands are ecosystem types that require specific environmental conditions in order to establish. This study indicates that restoration plantings most effectively establish under environmental conditions including elevations at least ½ m above MHHW, and average soil salinity values below 3 ppt. For the purpose of restoration planning, this study suggests that the depth to water table inversely relates with elevation. Higher elevation and lower salinity habitats led to increased woody planting success. Higher elevations may be able to support woody plant growth at elevated brackish salinities, and fresher salinities may be able to support woody plant growth at lower elevations. At this site, there were plantings installed into areas that did not support freshwater woody plant growth. In some cases, the plantings were purposely installed at elevations that were known to be too low, in order to determine the threshold elevation value at which to plant. However, in other cases, the plantings were installed at elevations that were thought to be sufficiently elevated. These middle-lower elevations, located on both sides of the river, lacked regular surface water flooding, but had elevated brackish ground water in the growing season.

Until more is known about the function and processes of tidal forested wetlands, all Pacific Northwest tidal swamp restoration projects would benefit from an overarching goal of science based management from the start. In this project, the determination to monitor plant response in relation to environmental controls was not decided upon until after plant installation. With an eye towards experimental design in preparing the sites, sourcing the plants and designing the planting plan, in addition to collecting data from the site prior to plant installation and immediately following installation, this study could have yielded additional insights into the environmental controls on woody plant success.

The very act of restoring hydrologic processes may allow the natural development of tidal swamps into the future. If we are able to gain an understanding of ecosystem drivers, it will be possible to speed up ecosystem progression and aid in successional development. By using the Nisqually Delta restoration as a living laboratory, we were able to test restoration assumptions and provide a framework for future tidal freshwater swamp restoration projects in Salish Sea estuaries.

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Appendix A: Nisqually River Estuary Restoration Plantings

Braget Property: All Plantings	**2008-2009 (29 ac)**	**2007-2008 (24 ac)**
Acer circinatum (vine maple)	63	585
Acer macrophyllum (blg-leafed maple)	526	535
Alnus rubra (red alder)	1784	2230
Cornus sericea (redosier dogwood)	200	245
Corylus cornuta (beaked hazelnut)	100	0
Crataegus douglasii (black hawthorne)	0	60
Fraxinus latifolia (Oregon ash)	735	891
Lonicera involucrata (twinberry)	980	528
Malus fusca (crabapple)	2574	1151
Oemleria cerasiformis (Indian plum)	1002	268
Myrica californica (wax myrtle)	0	100
Physocarpus capitatus (ninebark)	263	336
Picea sitchensis (sitka spruce)	1242	1057
Pinus contorta (shore pine)	0	487
Populus balsamifera ssp. trichocarpa (cottonwood)	1900	850
Psuedotsuga menzisii (Douglas-fir)	0	500
Rhamnus purshiana (cascara)	326	423
Ribes divaricatum (swamp gooseberry)	1330	600
Rosa nutkana (Nootka rose)	0	577
Rosa pioscarpa (swamp rose)	1330	600
Rubus spectabilis (salmonberry)	1002	535
Salix hookeriana (Hooker's willow)	2500	1650
Salix sp. (Pacific/Sitka willow)	1650	1325
Salix scouleriana (Scoulers willow)	526	1625
Sambucus racemosa (red elderberry)	852	571
Spirea douglasii (spirea)	0	500
Symphoricarpos albus (common snowberry)	1402	220
Thuja plicata (Western redcedar)	1752	738
Tsuga hetertophylla (Western hemlock)	0	200
Vaccinium ovata (evergreen huckleberry)	0	90
Totals	**22809**	**18877**

Table 7: Comprehensive list of restoration plantings installed on the east side of the river, Braget property. The 2007-2008 plantings were installed beyond of the range of tidal influence, and hence were outside the scope of this study.

Nisqually NWR: North Bench	2009-2010
Fraxinus latifolia (Oregon ash)	200
Malus fusca (Pacific crabapple)	300
Rosa pisocarpa (clustered rose)	400
Populus balsamifera ssp. trichocarpa (black cottonwood)	200
Lonicera involucrata (black twinberry)	50
Alnus rubra (red alder)	200
Salix sp. (Hooker's/Sitka/Pacific willows)	2500
Sub-Total	**3850**
Nisqually NWR: South Bench	**2009-2010**
Populus balsamifera ssp. trichocarpa (black cottonwood)	100
Salix sp. (Hooker's, Sitka and Pacific willow)	1700
Rosa pisocarpa (clustered rose)	100
Malus fusca (Pacific crabapple)	300
Sub-Total	**2200**
Nisqually NWR: Former Dike Footprint	**2009-2010**
Fraxinus latifolia (Oregon ash)	300
Alnus rubra (red alder)	300
Salix sp. (Pacific/Sitka/Hooker's willows)	1300
Malus fusca (Pacific crabapple)	300
Rosa pisocarpa (clustered rose)	400
Sub-Total	**2600**
Nisqually NWR: Northern Bench (interplantings)	**2010-2011**
Picea sitchensis (Sitka spruce)	200
Malus fusca (Pacific crabapple)	700
Lonicera involucrata (black twinberry)	800
Sub-Total	**1700**
Total of All Planting Areas	**10350**

Table 8: Comprehensive list of restoration plantings installed on the west side of the river, within the NNWR study sampling area. Additional plantings were installed in the winter of 2010-2011 and are outside the scope of this study. 2010-2011 plantings include: red alder, Oregon ash, black cottonwood, Oregon crabapple, Hooker's willow, Sitka willow, pacific willow, clustered rose, black twinberry and common snowberry.

Appendix B: Nisqually Tidal Swamp Reference Site Communities, 1980

Dominate Species	
Scientific Name	**Common Name**
Populus balsamifera ssp. trichocarpa	black cottonwood
Alnus rubra	red alder
Symphoricarpos albus	common snowberry
Minor Species	
Scientific Name	**Common Name**
Acer macrophyllum	bigleaf maple
Equisetum hyemale	horsetail (locally subdominant)
Oemleria cerasiformis	Indian plum
Ribes divaricatum	gooseberry
Rubus spectabilis	salmonberry

Table 9*: Populus balsamifera ssp. trichocarpa /Alnus rubra* and *Symphoricarpos albus* dominated reference community species (Burg, et al., 1980).

Dominate Species	
Scientific Name	**Common Name**
Populus balsamifera ssp. trichocarpa	black cottonwood
Alnus rubra	red alder
Rubus spectabilis	salmonberry
Sub-dominate Species	
Scientific Name	**Common Name**
Urtica sp.	nettles
Minor Species	
Scientific Name	**Common Name**
Acer macrophyllum	bigleaf maple
Acer circinatum	vine maple
Mahonia aquifolium (Pursh) Nutt.	Oregon Grape
Carex sp.	sedges
Clematis vitalba	old man's beard (Class C noxious weed)
Cornus stolonifera	red-osier dogwood
Corydalis scouleri	Scoulers corydalis
Oemleria cerasiformis	Indian plum
Ribes divaricatum	gooseberry
Sambucus racemosa	red elderberry
Polystichum munitum	sword fern
Dicentra formosa	Pacific bleeding heart
Galium sp.	bedstraw
Glecoma hederacea	creeping Charlie (non-native)
Claytonia sibirica L. var. *sibirica*	Siberian springbeauty

Table 10: Species identified in the *Populus balsamifera ssp. trichocarpa* /*Alnus rubra* and *Rubus spectabilis* dominated reference community (Burg, et al., 1980).

Appendix C: Statistical Analysis Coding for Variables

Code	Description	Unit	Range
totalplantedbyplot	Number of installed plants	individual plants	9 – 34
totalsurviveApr	Installed living plants in April	individual plants	0 – 31
totalsurviveOct	Installed living plants in October	individual plants	0 – 26
plotsurvive	Plants that survived until 10/2011	proportional	0 – 1
basalTotApr	Total basal area of plants, April	decimeters squared	0 – 2
basalTotOct	Total basal area of plants, Oct.	decimeters squared	0 – 3
changebasal	Change in basal area, 2011 season	proportional	-1 – 1
plotvigorapril	Mean vigor of living plants in April	qualitative categories	0.5 – 3
plotvigoroctober	Mean vigor of living plants in Oct.	qualitative categories	0.5 – 3
plotvigoravg	Overall mean vigor of living plants	qualitative categories	0.5 – 3

Table 11: Statistical analysis coding for response variables. All response variables were compiled into a summary value from individual installed trees and shrubs.

Code	Description	Unit
CRDO2	black hawthorne	*Crataegus douglasii*
ACMA3	big-leaf maple	*Acer macrophyllum*
FRPU7	cascara	*Rhamnus purshiana*
OECE	Indian plum	*Oemleria cerasiformis*
PHCA11	ninebark	*Physocarpus capitatus*
THPL	Western redcedar	*Thuja plicata*
SARA2	red elderberry	*Sambucus racemosa*
COSE16	redosier dogwood	*Cornus sericea*
RUSP	salmonberry	*Rubus spectabilis*
SASC	Scouler's willow	*Salix scouleriana*
PISI	Sitka spruce	*Picea sitchensis*
POBAT	black cottonwood	*Populus balsamifera ssp. trichocarpa*
LOIN5	black twinberry	*Lonicera involucrata*
ROPI2	clustered rose	*Rosa pisocarpa*
SAHO	Hooker’s willow	*Salix hookeriana*
FLRA	Oregon ash	*Fraxinus latifolia*
MAFU	Oregon crabapple	*Malus fusca*
SALAL	Pacific willow	*Salix lucida*
ALRU2	red alder	*Alnus rubra*
SASI2	Sitka willow	*Salix sitchensis*
SYAL	common snowberry	*Symphoricarpos albus*
WILL	willow not ID'ed to species	*Salix spp.*

Table 12: Coding for individual species installed in study plots. Species' morphological codes follow USDA Plants Database (2011).

Code	Description	Unit	Range
Site	Planting site; either NNWR or Braget Historic Farm. 1=NNWR, 2=Braget	categorical	1 or 2
East	Easting	meters	UTM 11 S
North	Northing	meters	UTM 11 S
Elev	Elevation above sea level (NAVD88)	meters	0 – 5
MHHW	Elevation above mean higher high water (Dupont tidal station, VDatum (NOAA, 2011a))	meters	-1 – 1
MLLW	Elevation above mean lower low water (Dupont tidal station, VDatum (NOAA, 2011a))	meters	0 – 5
Mulch	Is the plot was mulched with wood chips?	categorical	0=no, 1=yes
HerbApr	Cover class of herbaceous layer in 04/2011	categorical	1 -6
HerbOct	Cover class of herbaceous layer in 10/2011	categorical	1 -6
AvgSalin	Mean salinity of in situ soil water, measured bi-monthly in monitoring wells at low tide	ppt	0 – 16
Max Salin	Maximum salinity of in situ soil water	ppt	0 – 24
AvgDepWat	Mean depth to the water table from ground level measured in monitoring wells at low tide	meters	0 – 0.7
MaxDepWat	Max. measured depth to the water table	meters	0 – 0.7
MinDepWat	Minimum measured depth to the water table	meters	-0.2 – 0.7
soiltext	Clay + silt mineral soil content	proportional	0 - 1
SoilType	Soil texture class	categorical	loamy sand, sand, loam, silt loam and sandy loam
pH	pH of top 20 cm of soil	L/mol	3 - 6
OM	Organic matter in the top 20 cm of soil	proportional	0 - 1
BDens	Bulk density of top 20 cm of soil	g/cm^3	0 - 2
AvgSoilMois	Mean volumetric water content of soil	proportional	0 - 1
MaxSoilMois	Maximum volumetric water content of soil	proportional	0 - 1

Table 13: Statistical analysis coding for environmental variables. UTM stands for Universal Transverse Mercator, which is a geographic plane coordinate system. 11 S is code for the mapping zone in this coordinate system that includes southern WA State. In “MaxDepWat”, water table monitoring wells extended to a maximum depth of 70 cm below the surface of the ground. When the depth to the water table was deeper than 70 cm, depth of the well was entered. In “MinDepWat” values can be negative due to a confining aquifer. Wells extended 0 – 10 cm above the ground, and sometimes ground water levels filled the wells above the level of the ground surface.

Appendix D: PCA Tables

Variables	PC1	PC2	PC3
SoilMoisApr1	-0.003	0.201	0.223
SoilMoisMay1	0.027	0.180	0.236
SoilMoisMay2	0.024	0.208	0.206
SoilMoisJun1	-0.076	0.234	0.213
SoilMoisJun2	-0.079	0.239	0.098
SoilMoisJul1	-0.076	0.258	0.177
SoilMoisJul2	-0.095	0.274	0.043
SoilMoisAug1	-0.104	0.250	0.085
SoilMoisAug2	-0.063	0.225	0.154
SoilMoisSep1	-0.102	0.289	0.107
SoilMoisOct1	-0.211	0.082	0.116
SalinApr1	-0.158	-0.156	0.132
SalinMay1	-0.183	-0.035	0.246
SalinMay2	-0.194	-0.141	0.151
SalinJun1	-0.251	-0.146	0.131
SalinJun2	-0.237	-0.169	0.145
SalinJul1	-0.248	-0.162	0.069
SalinJul2	-0.240	-0.170	0.119
SalinAug1	-0.248	-0.122	0.040
SalinAug2	-0.246	-0.170	0.132
SalinSep1	-0.243	-0.176	0.127
SalinOct1	-0.159	-0.189	0.081
DepWatApr1	0.006	-0.139	0.151
DepWatMay1	0.140	-0.202	0.085
DepWatMay2	0.188	-0.165	0.041
DepWatJun1	0.219	-0.131	0.201
DepWatJun2	0.168	-0.157	0.206
DepWatJul1	0.186	-0.095	0.257
DepWatJul2	0.206	-0.098	0.283
DepWatAug1	0.189	-0.073	0.267
DepWatAug2	0.172	-0.097	0.250
DepWatSep1	0.194	-0.066	0.275
DepWatOct1	0.224	-0.022	0.197
Standard Deviation	**3.23**	**2.92**	**2.33**
Proportion of Variance	**32%**	**26%**	**16%**
Cumulative Proportion	**32%**	**57%**	**74%**

Table 14: PCA loading scores for top three PCs and summary statistics.

Plot	PC1	PC2	PC3
1	1.935	3.406	1.985
2	0.545	0.611	3.024
3	-1.917	0.571	3.155
4	0.686	2.572	1.813
5	1.197	3.486	2.527
6	2.505	0.552	0.644
7	2.206	2.203	2.024
8	4.221	-2.792	-1.982
9	1.985	-2.397	-2.056
10	-1.653	3.656	-3.872
11	-1.534	2.825	-3.642
12	-1.160	2.965	-3.335
13	-0.494	1.703	-3.603
14	-4.920	5.526	-4.612
15	-9.081	-0.067	0.196
16	0.649	-2.309	0.297
17	0.878	-3.383	-1.104
18	4.003	-1.712	-1.091
19	1.199	0.269	-2.443
20	0.415	3.421	1.598
21	-1.474	-3.097	0.073
22	-8.241	-6.621	1.883
23	3.324	-3.763	-1.523
24	-1.113	-1.276	0.565
25	0.214	-2.234	0.297
26	-6.451	-2.300	1.014
27	0.538	-3.561	1.152
28	0.902	2.123	2.812
29	-0.575	2.378	3.829
30	3.704	-4.546	-2.654
31	2.186	-0.684	-0.169
32	2.612	0.498	1.166
33	2.709	1.974	2.032

Table 15: PC scores for individual observations determined by PCA model, which were the assigned scores for new data points representing the soil moisture, soil salinity and depth to water table time series data.

Appendix E: Summarized Environmental Data

Site	Plot	Easting	Northing	Elev. (m MLLW)	Elev. (m MHHW)	Elev. (m NAVD88)	Depth to Water Table
Braget	1	522902.9888	5213825.715	4.77	0.62	3.63	0.57
Braget	2	522828.9767	5213842.631	4.60	0.45	3.46	0.6
Braget	3	522831.9847	5213866.111	4.52	0.37	3.38	0.54
Braget	4	522747.784	5213828.411	4.62	0.47	3.48	0.53
Braget	5	522674.4052	5213828.382	4.64	0.48	3.50	0.54
Braget	6	522601.6696	5213829.227	4.82	0.66	3.68	0.58
Braget	7	522525.0974	5213825.414	4.51	0.35	3.37	0.57
NNWR	8	522109.1794	5214052.858	4.68	0.52	3.54	0.63
NNWR	9	522126.421	5214099.772	4.50	0.34	3.36	0.52
NNWR	10	522141.2212	5214147.494	4.26	0.10	3.12	0.27
NNWR	11	522146.2673	5214196.83	4.29	0.13	3.15	0.29
NNWR	12	522149.8554	5214247.725	4.05	-0.11	2.91	0.3
NNWR	13	522160.1945	5214296.586	4.12	-0.04	2.98	0.3
NNWR	14	522163.2108	5214351.836	3.93	-0.22	2.79	0.15
NNWR	15	522100.2703	5214293.558	4.16	0.01	3.02	0.24
NNWR	16	522096.1515	5214243.832	4.64	0.48	3.50	0.56
NNWR	17	522089.0145	5214194.331	4.67	0.51	3.53	0.56
NNWR	18	522082.3667	5214144.68	4.69	0.53	3.55	0.61
NNWR	19	522076.6369	5214095.18	4.41	0.25	3.27	0.47
NNWR	20	522069.8914	5214045.625	4.59	0.43	3.45	0.54
NNWR	21	522041.9915	5214086.966	4.46	0.30	3.32	0.48
NNWR	22	522036.4229	5214139.273	4.23	0.07	3.09	0.43
NNWR	23	522004.1446	5214120.109	4.75	0.59	3.61	0.66
NNWR	24	521956.4154	5214144.443	4.48	0.32	3.34	0.56
NNWR	25	521947.4576	5214195.624	4.59	0.43	3.45	0.61
NNWR	26	521975.3949	5214158.512	4.39	0.23	3.25	0.36
Braget	27	522452.1722	5213825.24	4.86	0.70	3.72	0.61
Braget	28	522456.9777	5213841.207	4.63	0.47	3.49	0.56
Braget	29	522461.2345	5213858.147	4.57	0.41	3.43	0.54
Braget	30	522379.6342	5213825.123	5.74	1.58	4.60	0.67
Braget	31	522385.4336	5213846.439	4.83	0.67	3.69	0.59
Braget	32	522391.139	5213865.696	4.66	0.50	3.52	0.6
Braget	33	522400.2213	5213904.917	4.70	0.54	3.56	0.58

Table 16: Plot level summarized data: Easting, northing, depth to water table and elevations in MLLW, MHHW and meters above sea level for all sites. The easting and northing location information are in UTM 11 S. Lower restoration success plots, including cluster analysis groups 3, 4 and 5, are shaded.

Site	Plot	% Sand	% Silt	% Clay	Texture Class
Braget	1	57%	38%	5%	sandy loam
Braget	2	79%	18%	3%	loamy sand
Braget	3	83%	14%	3%	loamy sand
Braget	4	73%	24%	3%	loamy sand
Braget	5	65%	30%	5%	sandy loam
Braget	6	72%	23%	5%	sandy loam
Braget	7	66%	27%	7%	sandy loam
NNWR	8	64%	27%	8%	sandy loam
NNWR	9	65%	28%	7%	sandy loam
NNWR	10	61%	29%	10%	sandy loam
NNWR	11	37%	48%	15%	loam
NNWR	12	51%	43%	5%	sandy loam
NNWR	13	66%	28%	5%	sandy loam
NNWR	14	55%	36%	9%	sandy loam
NNWR	15	43%	50%	7%	silt loam
NNWR	16	53%	41%	5%	sandy loam
NNWR	17	66%	31%	3%	sandy loam
NNWR	18	56%	40%	3%	sandy loam
NNWR	19	90%	9%	1%	sand
NNWR	20	68%	29%	3%	sandy loam
NNWR	21	79%	18%	3%	loamy sand
NNWR	22	65%	30%	5%	sandy loam
NNWR	23	62%	34%	4%	sandy loam
NNWR	24	62%	33%	5%	sandy loam
NNWR	25	53%	40%	7%	sandy loam
NNWR	26	62%	33%	5%	sandy loam
Braget	27	81%	18%	1%	loamy sand
Braget	28	61%	36%	3%	sandy loam
Braget	29	54%	42%	4%	sandy loam
Braget	30	75%	22%	3%	loamy sand
Braget	31	66%	31%	3%	sandy loam
Braget	32	64%	31%	5%	sandy loam
Braget	33	55%	40%	5%	sandy loam

Table 17: Soil texture test results from study plots. Soil textures at the plots were generally sandy loams or loamy sands. Lower restoration success plots, including cluster analysis groups 3, 4 and 5, are shaded.

Site	Plot	pH	% OM	Bulk Density (g/cm³)	% Soil Moisture	Salinity (ppt)	Herb. Cover
Braget	1	4.83	9.0%	1.1	53.1%	0.17	5.5
Braget	2	5.8	12.6%	0.6	46.3%	3.38	6.0
Braget	3	5.34	14.4%	0.8	48.1%	6.40	6.0
Braget	4	5.3	8.4%	1.2	48.6%	2.00	6.0
Braget	5	5.67	13.4%	1.1	51.4%	1.00	5.5
Braget	6	5.32	7.4%	1.1	36.0%	1.00	6.0
Braget	7	5.32	8.8%	1.4	43.8%	0.75	6.0
NNWR	8	4.14	4.1%	1.3	17.4%	0.00	2.0
NNWR	9	3.9	4.9%	1.2	21.8%	1.83	2.5
NNWR	10	4.08	8.7%	1.1	42.7%	0.70	4.5
NNWR	11	3.65	6.5%	1.2	39.7%	1.27	5.0
NNWR	12	3.95	6.0%	1.1	40.7%	0.80	4.0
NNWR	13	3.92	3.7%	1.4	33.6%	0.73	4.5
NNWR	14	4.4	11.0%	1.2	53.8%	1.82	5.0
NNWR	15	4.41	7.8%	1.1	47.2%	11.09	5.0
NNWR	16	4.24	7.3%	1.3	28.7%	4.50	2.0
NNWR	17	4.31	5.7%	1.3	21.7%	4.50	4.5
NNWR	18	4.99	5.6%	1.1	22.8%	0.00	3.5
NNWR	19	4.84	1.7%	1.5	29.1%	0.81	5.5
NNWR	20	5.08	8.5%	1.1	54.4%	1.50	1.5
NNWR	21	4.17	4.3%	1.5	25.0%	7.00	6.0
NNWR	22	4.21	4.8%	1.3	31.0%	15.67	5.5
NNWR	23	4.42	7.4%	0.8	18.2%	1.90	1.5
NNWR	24	4.47	10.0%	1.4	38.0%	6.00	6.0
NNWR	25	4.63	9.5%	1.4	33.8%	5.00	5.5
NNWR	26	5.17	5.1%	1.1	36.7%	11.45	1.5
Braget	27	5.46	4.4%	1.2	25.7%	5.50	6.0
Braget	28	5.09	5.8%	1.1	48.3%	2.33	5.5
Braget	29	5.21	8.3%	1.1	54.6%	3.67	5.0
Braget	30	5.14	4.8%	1.3	14.5%	1.11	6.0
Braget	31	5.75	5.3%	1.3	33.1%	1.45	6.0
Braget	32	5.66	8.6%	1.4	37.9%	1.00	6.0
Braget	33	5.31	7.1%	1.1	42.8%	0.50	6.0

Table 18: Plot level summarized data: Soil characteristics test results from study plots and herbaceous cover. Soil moisture and salinity values are averaged from 11 values per plot, collected semimonthly, May through October 2011. Herbaceous cover values (Table 4) are averaged from two dates for each plot, from the beginning and end of the growing season. Lower restoration success plots, including cluster analysis groups 3, 4 and 5, are shaded.

Appendix F: Summarized Plant Response Data

Site	Plot	Survivorship	Initial B. A.	Change in B. A.	Vigor
Braget	1	88%	0.56	0.12	2.10
Braget	2	18%	0.12	0.32	1.67
Braget	3	10%	0.03	0.85	2.00
Braget	4	38%	0.48	-0.40	1.50
Braget	5	50%	0.52	0.26	2.00
Braget	6	88%	0.88	0.55	1.89
Braget	7	50%	0.24	0.37	1.69
NNWR	8	45%	0.11	-0.66	1.31
NNWR	9	63%	0.37	-0.34	1.49
NNWR	10	67%	0.30	0.12	2.05
NNWR	11	33%	0.05	-0.40	1.34
NNWR	12	20%	0.05	0.39	1.00
NNWR	13	23%	0.26	0.54	1.11
NNWR	14	78%	0.16	0.09	1.65
NNWR	15	0%	0.00	0.00	0.00
NNWR	16	55%	0.14	-0.59	1.38
NNWR	17	67%	0.22	0.00	1.63
NNWR	18	64%	0.29	-0.17	1.85
NNWR	19	24%	0.17	-0.71	1.21
NNWR	20	65%	0.54	0.09	1.95
NNWR	21	32%	0.13	-0.78	1.24
NNWR	22	0%	0.00	0.00	0.01
NNWR	23	52%	0.21	0.42	1.37
NNWR	24	76%	1.30	0.18	1.71
NNWR	25	77%	0.56	1.4	1.45
NNWR	26	17%	0.00	1.1	1.00
Braget	27	78%	0.30	1.2	2.03
Braget	28	47%	0.36	1.1	1.80
Braget	29	43%	0.14	1.1	1.25
Braget	30	72%	0.69	1.3	1.92
Braget	31	81%	0.77	1.3	2.08
Braget	32	89%	1.52	1.4	2.00
Braget	33	73%	0.65	1.1	1.89

Table 19: Plot level summarized data: Plant responses. B. A. stands for basal area and "Change in B.A." represents plant growth. Lower restoration success plots, including cluster analysis groups 3, 4 and 5, are shaded.

Appendix G: Photo Documentation of Plots

	
Plot 1 – 10/04/2011	Plot 2 – 10/04/2011
	
Plot 3 – 10/04/2011	Plot 4 – 10/04/2011
	
Plot 5 – 10/04/2011	Plot 6 – 10/04/2011

	
Plot 7 – 10/04/2011	Plot 8 – 10/04/2011
	
Plot 9 – 10/04/2011	Plot 10 – 10/04/2011
	
Plot 11 – 10/04/2011	Plot 12 – 10/04/2011

Plot 13 – 10/04/2011

Plot 14 – 10/04/2011

Plot 15 – 10/04/2011

Plot 16 – 10/04/2011

Plot 17 – 10/04/2011

Plot 18 – 10/04/2011

Plot 19 – 10/04/2011

Plot 20 – 10/04/2011

Plot 21 – 10/04/2011

Plot 22 – 10/04/2011

Plot 23 – 10/04/2011

Plot 24 – 10/04/2011

	
Plot 25 – 10/04/2011	Plot 26 – 10/04/2011
	
Plot 27 – 10/04/2011	Plot 28 – 10/04/2011
	
Plot 29 – 10/04/2011	Plot 30 – 10/04/2011

	
Plot 31 – 10/04/2011	Plot 32 – 10/04/2011
	
Plot 33 – 10/04/2011	

Table 20: Photo documentation of the study plots. All photos were taken with a bearing of due north from the south boundary of the plot, looking towards the plot center.