Is Sweetgrass on the Decline?
Response of *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith to Environmental Variables, Cultural Use, and Anthropogenic Change in Grays Harbor, Washington

Caren Jane Crandell

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Reading Committee:
Kern Ewing, Chair
Charles Simenstad
Elizabeth Van Volkenburgh

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Abstract

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

The bulrush *Schoenoplectus pungens* is native to the brackish marshes of the Pacific Northwest and is used by Native Americans in basketry. Called sweetgrass by local weavers, the clonal species dominates portions of Grays Harbor National Wildlife Refuge in Washington and displays enormous variation across the landscape and sometimes within the space of a few centimeters. The refuge has become the region's primary gathering ground for sweetgrass, but in the last two decades, weavers have become concerned about the quality of the material they collect.

In the first chapter I explore the environmental variables that contribute to the variation in *S. pungens* characteristics. Data was collected along ten transects and analyzed using principal components analysis and multiple regression with a Specified Analysis Plan to minimize Type I error. Maximum stem height was more responsive to the measured variables than other plant attributes and was positively associated with percent sand, percent moisture, and sulfide, when confounding factors were accounted for. It was negatively associated with elevation (inundation class), salinity, percent macro-organic matter (MOM), and redox potential*.* Stem density was positively associated with elevation (inundation class), percent sand, and moisture, when confounding factors were accounted for. Stem density was negatively associated with percent MOM. Stem caliber was negatively associated with elevation (inundation class). Aboveground (AG) biomass was positively associated with elevation (inundation class), percent sand, and moisture when confounding factors were accounted for. The elevation optimum appeared to shift from a higher to a lower elevation zone between 1999 and 2006, possibly as a result of sedimentation that "raised the floor" of the marsh.

In the second chapter, I report the results of an *in situ* multi-year randomized block experiment conducted at four sites to determine what harvest regime(s) may be sustainable for sweetgrass. Two intensities (100% and 25% stem harvest) and two frequencies (one and two consecutive years of harvest) were tested, including a year of rest following one year of harvest. Our results lead us to conclude that a) at least one year of rest after harvest is important for the plant's recovery; b) selective harvest of 25 percent of stems in a patch, with at least one year of rest following harvest, does not appear to have a negative impact on plant attributes; and c) stems over 130 cm may not be affected by harvest.

Finally, I examine the environmental history and cultural geography of sweetgrass in Grays Harbor from the 1800's to the present. I propose that the plant migrated along the shoreline in response to anthropogenic change and the weavers followed, adapting to changing conditions as they have for millennia. I also address factors in surrounding watersheds that contributed to a convergence of harvesting on the shores of the wildlife refuge. To account for these adaptive shifts and ensure access of Native American weavers to this important cultural resource, I suggest that, as time passes, gathering grounds be understood functionally rather than strictly geographically.

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CHAPTER 1. Response of *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith to Environmental Variables in the Estuarine Marsh of Grays Harbor National Wildlife Refuge, Washington

ABSTRACT

The bulrush *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith is a culturally important plant that exhibits enormous variation within the estuarine marsh of Grays Harbor National Wildlife Refuge (GHNWR), Washington. Tidal marshes are characterized by complex environmental gradients, and the purpose of this study was to determine what physical and chemical factors can explain the observed variation in *S. pungens* attributes. Forty-three sampling stations were established along ten transects oriented parallel to the elevation gradient in *S. pungens* stands on the north and south shores of the wildlife refuge. Maximum stem height, stem density, stem caliber, and aboveground (AG) biomass were measured annually over ten years in a monitoring study. Environmental variables were measured at permanent sampling points for two years of that study (1999 and 2006). Plant and environmental data was analyzed using principal components analysis and multiple regression with a Specified Analysis Plan to minimize Type I error. Maximum stem height was more responsive to the measured variables than other plant attributes and was positively associated with percent sand, percent moisture, and sulfide, when confounding factors were accounted for. It was negatively associated with elevation (inundation class), salinity, percent macro-organic matter (MOM), and redox potential. Stem density was positively associated with elevation (inundation class), percent sand, and moisture, when confounding factors were accounted for. Stem density

was negatively associated with percent MOM. Stem caliber was negatively associated with elevation (inundation class). Aboveground (AG) biomass was positively associated with elevation (inundation class), percent sand, and moisture when confounding factors were accounted for. In general, taller and thicker stems grew at lowest elevation and shorter and thinner stems grew at highest elevation. The elevation optimum for AG biomass production appeared to shift from a higher to a lower elevation zone between 1999 and 2006, possibly as a result of sediment accretion that raised the "floor" of the marsh.

Changes in environmental conditions may bring more changes to sweetgrass that affect the weavers. Although *S. pungens* can likely withstand an increase in tidal inundation better than many marsh species, it is vulnerable to sea-level rise over the long term because of the topographic and infrastrucural constraints on marsh migration at GHNWR. Successful re-establishment of *S. pungens* has been limited in Washington State, possibly due to lack of information about the multi-dimensional conditions under which the species is typically dominant and able to outcompete other species. This work contributes to our understanding of the complex gradients to which existing *S. pungens* stands are responding and that must be considered in restoration efforts that provide both cultural and ecological services.

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INTRODUCTION

Coastal marshes are valued for the cultural and ecological services they provide but are increasingly vulnerable to sea-level rise, urbanization, and watershed alteration. The Grays Harbor National Wildlife Refuge on the coast of Washington was established to preserve habitat for migrating shorebirds. For decades, it has also been a gathering ground for Native American weavers that use *Schoenoplectus pungens*, which they call sweetgrass, in basketry. When these weavers expressed concern to the U. S. Fish and Wildlife staff that the sweetgrass was on the decline (e.g., getting shorter, diminishing in area), the USFWS began an effort to determine the status of the species. I mapped the species in the refuge in 1999 and began a monitoring program that lasted ten years. I collected data on a variety of plant attributes, mindful that weavers and ecologists might key on different features as "indicators of wellness" (Lake 2015:xi). While mapping the species in the refuge and exploring the shores of Grays Harbor, I saw the wide range of stem heights, stem density, etc., across the landscape. Trying to understand the environmental drivers behind that variation – and possibly what was affecting the qualities that weavers cared about – was a natural next step. During the first year of the monitoring study (1999), I collected data on physical environmental variables along with plant characteristics, and then in 2006 I focused primarily on chemical environmental variables during the growing season. An added benefit of the work was that what we learned could be put to use in restoration efforts undertaken by Native American tribes in the region.

This chapter provides an ecological foundation for the subsequent chapters on sustainable harvest of sweetgrass and the story of how Bowerman Basin became the region's primary sweetgrass harvesting ground. In the following sections, I provide background on *S. pungens* and some close relatives, the work of others on the species and environmental factors in Pacific Northwest marshes, *S. pungens* growth forms, and the weavers' use of sweetgrass and concern about its decline. I paid special attention to sulfide because of its potential dual role as both nutrient and toxin and because little work had been done on this environmental variable in Pacific Northwest systems.

Phenotypic Variation of *Schoenoplectus pungens*

The intertidal bulrush *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith dominates the lowest elevations of the brackish estuarine marshes of the Pacific Northwest (Figure 1-1). These coastal environments are complex, and multiple physical and chemical variables influence species distribution and plant growth (Disraeli and Fonda 1979, Hutchinson 1982, Ewing 1986). *S. pungens* creates large clonal stands that extend in bands along the shoreline or deltaic foreshore. At Grays Harbor National Wildlife Refuge in Grays Harbor, Washington, the species exhibits a wide range of stem heights and densities across the landscape and on the north and south shores of Bowerman Basin (Figure 1-2). Stems are tall and robust (thick) at lower elevation and shorter, skinnier and denser at higher elevation, with variations along the elevation gradient and in anoxic pannes (personal observation; see also Ewing 1986). For example, in pure stands at the peak of a single growing season (21 August 2007), stem heights ranged from 22 to 173 cm; stem densities ranged from 13 to 249 stems in a 25-by-25 cm quadrat; stem calibers ranged from 2.46 to 8.92 mm; and aboveground (AG) biomass ranged from 24.8 to 93.7 g per quadrat. The two extremes constitute two forms of the species, sometimes within centimeters of each other. These differences have been shown, through reciprocal transplants, to be phenotypic variation expressed by a few genotypes in response to environmental conditions, rather than by genetically distinct ecotypes that are adapted to conditions in particular locations (Seliskar 1990, Karagatzides and Hutchinson 1991). This morphological variation provides evidence of a heterogeneous environment. The plasticity of the species may be an adaptation that enables it to handle a variety of stresses and "colonize a wide range of habitats" (Ikegami et al. 2007:248) or to acquire resources in an environment "with a more stable patch structure" than would be found in a system receiving nutrients in "unpredictable pulses" (de Kroons and Hutchings 1995:150). In other words, species that are clonal and plastic may be best able to colonize and survive in the dynamic marsh mosaic.

***S. pungens* and Environmental Variables in Previous Studies in Pacific Northwest Marshes**

Studies in the Pacific Northwest have identified environmental variables that affect the distribution and attributes of *S. pungens.* In the Nooksack River delta, Disreali and Fonda (1979) found the *S. pungens* (formerly *Scirpus americanus*) zone to be located at lower elevations characterized by daily tidal inundation, coarse soil texture (i.e., sand), and lower soil moisture (due to the coarser texture). Elevation in and of itself has an effect only through its association with these other factors. In the Fraser River delta, Hutchinson (1982) determined that primarily elevation and secondarily salinity, soil texture and soil moisture were influencing factors. At the low end of its elevation range, *S. pungens* dominated in well-draining sandy areas with relatively low soil moisture and that, at the middle and high end of its range, it was limited to sandy, well-drained areas of moderate salinity (approximately 8-15 ppt). In the Skagit River delta, elevation, salinity, soil texture, macro-organic matter and redox potential were associated with variation in *S. pungens* growth (Ewing 1986). *S. pungens* dominated sites of relatively low elevation and higher salinity (8-12 ppt). Salinity was negatively associated with biomass per shoot of *S. pungens* and positively associated with stem density. Percent macro-organic matter in substrate was negatively associated with AG biomass. Although not a linear association between environmental and plant variables, redox potential was lowest in pannes, or small depressions, with high AG production and robust stem morphology.

S. pungens **and Congeneric Species in Other Regions**

In other regions of North America, the species variant is *S. pungens* (Vahl) Palla var. *pungens* or *S. pungens* var. *longispicatus* (Britton) S. G. Smith, but research on the influence of environmental variables is relevant to the current study. In James Bay in eastern Canada, Ewing and others found that *S. pungens* var. *pungens* dominated low elevations in areas along the banks and channels of the Harricanaw River, where freshwater inputs reduced salinity to 0-2 ppt (Ewing and Kershaw 1986, Ewing et al. 1989). Most of the environmental factors presented in previous studies were noted as affecting distribution of plant communities in this marsh, but variation within *S. pungens* populations was not presented. To the south in the St. Lawrence River estuary, Deschenes & Serodes (1985) looked at the interaction of salinity and elevation in terms of duration of submersion. Salinity affected the amount of submersion that *S. pungens* var. *pungens* would withstand. The more saline the environment, the less submersion (35% of the time during summer sampling period) it could tolerate, and higher the species grew in the tidal range; the lower the salinity, the more submersion (75%) the species could tolerate, and the farther it extended toward the low water mark. Although this study did not look at variation in plant attributes across the elevation gradient, it did consider elevation in a functional way, i.e., in terms of a physical factor that varies with elevation.

Role of Sulfides in Growth of Marsh Plants

Sulfur must be considered in estuarine marshes because high levels of sulfate compounds in sea water can be chemically reduced to sulfide, which can be toxic to plants (Reddy and DeLaune 2008:449-450, Mitsch and Gosselink 2015:194). In coastal and marine ecosystems, abundant sulfate, an inorganic oxidized form of sulfur, is accessible to plants in the substrate and water. Plants take up sulfates and chemically reduce them in the process of incorporating them into amino acids used to build proteins (Larcher 1995:183, 417; Reddy and DeLaune 2008:447, 453-4). In areas of low redox potential within in the intertidal marsh environment, sulfates can be chemically reduced to sulfides. Sulfate requires active transport, whereas sulfide is absorbed passively by plants, and sulfate is actively taken up when sulfide is not available in sufficient quantities (Davidian and Kopriva 2010; Cronk and Fennessey 2001:78; Mitsch and Gosselink 2015:224;). In anaerobic environments, high concentrations of sulfides can inhibit plant growth by interfering with alcohol dehydrogenase (ADH), which catalyzes the final step in fermentation (Mitsch and Gosselink 2015:224-5). If this anaerobic respiration process is interrupted, less energy is released and nitrogen uptake, which requires energy, decreases (Cronk and Fennessey 2001:141). Growth is thus inhibited. In addition, sulfide interferes with energy release of aerobic respiration by inhibiting cytochrome *c* oxidase, which is the enzyme in the final step of electron transport to oxygen (Maricle et al. 2006). Again, less energy leads to less nitrogen uptake and growth. Wetland plant adaptations such as aerenchyma help maintain levels of oxygen in roots, which mitigates sulfide exposure. Detoxifying mechanisms possessed by some species include release of hydrogen sulfide and other volatile compounds, enzyme-catalyzed oxidation, and associations with sulfur-oxidizing bacteria, though more work on these mechanisms is needed (Cronk and Fennessey 2000:114; Mitsch and Gosselink 2015:224, 280).

Sulfides have been shown to be negatively associated with growth of marsh species in Alabama, Louisiana and Georgia (Lee et al. 1999, Koch and Mendelssohn 1989, Bradley and Dunn 1989, respectively). Although sulfur is a plant nutrient, its chemically reduced form, sulfide, can be toxic to some species above certain concentrations. It interferes with anaerobic energy production and nitrogen uptake (Koch et al. 1990). Sulfide levels have been found to be higher on poorly draining marsh plains than on tidal creek banks that are frequently flooded but drain quickly (Bradley and Dunn 1989).

Schile et al.'s (2017) work in San Francisco Bay is one of few West Coast studies that have included sulfides among environmental factors with potential effects on vegetation. However, the study contrasted a delta island with higher salinity and an inland marsh with lower salinity, rather than the creeks and plains of a marsh complex. Further, sulfides were not different enough at the two sites and did not appear to affect plant growth, or at least were not discussed in any detail. Concentrations were so low that they were reported in hundredths of parts per million (e.g., 0.01 to 0.07 ppm), equivalent to very low micromolar units (0.1-2.188 μM). In a greenhouse study, Maricle et al. (2006) looked at anoxia tolerance in seven marsh grass species, including *Distichlis spicata* from northern Puget

Sound and two invasive species of *Spartina* from Puget Sound and Willapa Bay. High marsh species, such as *Distichlis*, exhibited high rates of aerobic respiration and therefore sensitivity to sulfide, which interferes with aerobic respiration. The two invasive species typical of the low marsh exhibited low rates of aerobic respiration, enhanced ability to respire anaerobically, and greater tolerance of sulfides. This study looked at the effect of sulfide on physiological processes, e.g., production of enzymes, but not the growth of any species. Karagatzides and Hutchinson (1991) contrasted high and low portions of monotypic stands of *S. pungens* (formerly *Scirpus americanus*) and *Bolboschoenus maritimus* (formerly *Scirpus maritimus*) in the Fraser River delta and found that sulfides were lower at low elevations of *S. pungens* than at high elevations, whereas the opposite was true of *B. maritimus*. Sulfide concentrations were determined in substrate pellets using an elemental analyzer and then integrated with bulk density measurements, so the mean values of 1.88 mg/cm^3 in the low *S. pungens* marsh and 2.77 mg/cm^3 in the high *S. pungens* marsh are difficult to compare to results of other studies. AG biomass was lower where sulfides were lower, but the effect of sulfide was not statistically analyzed. The researchers in the Fraser River study suggested that sulfide potentially had a greater effect on *B. maritimus*, which occupied fine-textured organic-rich substrate (Karagatzides and Hutchinson 1991). So we still know little about the role of sulfide in vegetation growth in West Coast marshes.

The sulfide level that has an effect appears to differ with the species, though results are not consistent. In a hydroponic culture experiment, Bradley and Dunn (1989) showed that sulfide concentrations of 0.5 mM affected biomass production in *Borrichia frutescensI* (bushy seaside tansy), and 1 mM affected height and biomass of *Spartina alterniflora* (smooth cordgrass). In a greenhouse experiment, Koch and Mendelssohn (1989) demonstrated that a concentration of 1 mM decreased stem, root and rhizome biomass in *Panicum hemitomon* (maidencane, a freshwater wetland species) but decreased only root biomass in *Spartina alterniflora*. However, in another greenhouse experiment, Otte and Morris (1994) exposed *S. alterniflora* to a range of sulfide concentrations up to 2 mM, and none affected the plant's fresh weight of shoots or roots. In a third controlled study, Pezeshki et al. (1991) found that much lower levels of hydrogen sulfide concentrations affected net carbon assimilation, as measured by CO_2 assimilation: *P. hemitomon* was sensitive to hydrogen sulfide concentrations exceeding 0.22 mg H_2S/L (6.47 μM), and *S. patens* (saltmeadow cordgrass) was sensitive to hydrogen sulfide concentrations exceeding 0.34 mg H_2S/L (100 μM). Ewing et al. (1997) found that sulfides were negatively correlated with shoot elongation in brackish *S. patens* marshes of coastal Louisiana, where mean sulfide concentrations ranged from 0.09 to 2.038 ppm (2.9-67.93 μM) during the months of most rapid growth.

This environmental factor received special emphasis in the current study because of the paucity of sulfide work conducted in Pacific Northwest marshes and because of sulfide's dual effect on plant growth. As explained earlier, it functions as both a nutrient, or growth stimulant, at lower concentrations and as a toxin, or growth inhibitor, at higher concentrations (Cronk and Fennessey 2001:113, 141; Davidian and Kopriva 2010; Mitsch and Gosselink 2015:224). Sulfide may play a role in the difference between tall and short growth forms, as proposed in the next section.

Growth Forms of *S. pungens* and Effect of Sulfide

At Grays Harbor National Wildlife Refuge, a pattern in sweetgrass growth forms is readily visible in most monotypic stands in the landscape: tall stems grow at low elevations and stems at higher elevations are shorter (personal observation). Albert et al. (2013) described *S. pungens* stems in lower zones that were twice as tall as those in higher zones in estuarine marshes of the Tillamook Bay, Oregon. Ewing (1986) reported two growth forms of *S. pungens* (then called *Scirpus americanus*), though the tall, robust form was found in anoxic pannes in less saline portions of the Skagit River delta marsh as opposed to at the low end of the elevation gradient. (Pannes, which are small depressions, remain inundated or saturated at low tide, so conditions are more similar in some ways to those at low elevations than the higher marsh surrounding the pannes.) The differences in growth forms – that are really two ends of a spectrum – are of additional interest because of the cultural use of the sweetgrass: weavers notice height more than most other attributes and prefer taller stems, which they harvest primarily at lower, muddier elevations (Jones 1977:3; Shebitz and Crandell 2012; L. Ryan and T. Ryan, personal communication).

Previous studies have focused on the effects of geomorphology, specifically tidal creek banks versus inner marsh, on sulfide concentrations (Bradley and Dunn 1989). Tidal creek banks are regularly flooded but drained quickly, leading to aerated substrates, high redox potential, and low sulfides; whereas inner marshes or marsh plains are inundated less frequently by tides but remain saturated in a way that results in low oxygen levels, low redox potential, and higher sulfide concentrations. Tidal creeks are not a prominent feature in the monotypic stands of sweetgrass in GHNWR or those elsewhere in Grays Harbor. However, we can try to apply what is known about environmental conditions in tidal creek-inner marsh mosaics to differences in sulfide concentrations over the elevation gradient and potentially create differences in growth forms of sweetgrass. At low elevations, the substrates are regularly inundated by the tide, which could lead to low redox potential; however, tides also both bring in oxygenated water, raising redox potentials, and carry away "excess" sulfides (Howes et al. 1986, Reddy and DeLaune 2008:473- 4). At low or moderate sulfide levels, sulfides are an easily obtained source of a nutrient. By contrast, sulfides might accumulate at higher elevations that are less frequently inundated by tides but that might remain saturated where topography is flat enough, the soil texture is fine enough (i.e., less sandy), or overland flow or groundwater is another source of moisture. Higher levels of sulfide might inhibit stem growth, resulting in the shorter form of the plant at higher elevations. Taken together, these conditions may contribute to the observed pattern of taller stems at lower elevations.

Cultural Use and Possible Decline of Sweetgrass

In addition to the ecological context, the variation in plant characteristics are of cultural interest because Native Americans in the Pacific Northwest use the plant in their basketry (Shebitz and Crandell 2012; Figure 1-3). In the last century, Bowerman Basin has become the primary gathering ground for sweetgrass in Western Washington (see Chapters 2 and 3). In 1996, the U. S. Fish and Wildlife Service (USFWS) established GHNWR in Bowerman Basin. The agency then learned about the concern of some Native American weavers about the decline of sweetgrass, possibly due to overharvesting or pollution (Seto, personal communication; Ryan 2000). "Decline" was not formally defined, but in conversations over several years, I determined that weavers were referring to decreases in some combination of height, suppleness, height to width ratio, and spatial extent, as well as "spotting" (L. Ryan, personal communication; T. Ryan, personal communication; Thadei, personal communication; Harradine, personal communication; Lamberson 1996). Although different stem sizes may be used for different projects, longer stems and those with a high length-width ratio are generally preferred.

Role of *S. pungens* in Habitat

USFWS does not use sweetgrass, of course, but was interested in its condition or fate in the context of the habitat that their mandate requires them to protect (Grays Harbor Refuge Planning Team 1990:1). The weavers' concern about decline prompted the Federal land managers to wonder if the habitat for shorebirds, especially, was changing or deteriorating (Seto, personal communication). Marsh vegetation provides habitat for some species, such as marsh wrens that feed on insects and find cover in the vegetation (personal observation), but the flocks of shorebirds that frequent the mudflats of Bowerman Basin are affected indirectly by vascular plant production. Decomposing biomass provides the largest portion of the organic carbon at the base of the food web in the estuary (Newell and Porter 2000; Mitsch and Gossselink 2015:282; but see Kreeger and Newell (2000) re the contributions of phytoplankton and benthic algae). The detrital process starts with fungal decomposers of senescing stems, which are then shredded by snails and amphipods that drop plant-fungal fragments to the substrate surface, where bacteria continue to break down the material. This mix, along with seasonally available algae on the plant stems and substrate surface, is consumed by meiofaunal deposit feeders, including those that form the bulk of the shorebirds' prey. Since *S. pungens* contributes to the ecosystem food web through a detrital pathway, aboveground biomass would be the focus of an ecologist interested in the condition sweetgrass. In other words, the "indicators of wellness" (Lake 2015:xi) would be different from what weavers focus on.

Purpose of Study

This purpose of this study was to determine what physical and chemical variables affect growth of *S. pungens*, as measured by attributes that matter to weavers as well as ecologists. Given that environmental variables interact, I hypothesized that one or more plant attributes would be associated with some combination of the following variables: soil texture, soil moisture, macro-organic matter, inundation class (elevation), salinity, redox potential, pH, and pore water temperature, with a special emphasis on sulfides. This study was conducted during 1999 and 2006 in tandem with a ten-year monitoring study established to track the "indicators of wellness" (Lake 2015:xi) of sweetgrass in GHNWR.

STUDY AREA

The study region was Grays Harbor estuary in Washington, a classic drowned river-mouth estuary where the Chehalis, Hoquiam, Humptulips and Elk Rivers, among others, meet the Pacific Ocean (Figure 1-2). The Grays Harbor National Wildlife Refuge (GHNWR) is located on the northern shore of the inner bay, which experiences greater exposure to wind and wave energy than some other shorelines within the bay. These conditions are consistent with Dethier's (1990:33, 35) use of *S. pungens* as a diagnostic species of estuarine intertidal sand or mixed-fine and mud sites (i.e., partly enclosed, eulittoral, mesohaline marsh). GHNWR hosts some of the largest stands of sweetgrass in Grays Harbor (personal observation).

Bowerman Basin is a manmade basin created by the construction of an airport strip (initially a World War II military air base) where the mudflats meet a deeper channel on the northern side of the inner bay (Figure 1-4). Additional fill between the shoreline and the airport causeway occurred with the deposition of sediments dredged from the commercial channels within the harbor (Grays Harbor Refuge Planning Team 1990; see Chapter 3).

METHODS

Field Methods and Laboratory Analysis

Ten transects were established within sweetgrass stands on the north and south shores within GHNWR in 1999 (Figure 1-4). The transects were placed perpendicular to the shoreline and parallel to the elevation gradient. They were located within the largest monotypic stands of sweetgrass and positioned to capture the maximum amount of variation within the boundaries of the wildlife refuge. Eight were located along the north shore and two on the south shore. While the full spectrum of variation was captured on the north shore, the GHNWR boundary on the airport strip limited the number of transects that could be set up in the large sweetgrass stand that extends around the western end of the airport strip (Figure 1-4).

Transects ranged from 18 meters (Transect N8) to 46 meters long (Transect N5 and N7). Permanent sampling points along the transect were set up a) one meter down-slope from the high edge of the stand, b) one meter up-slope from the low edge of the stands, and c) at two or three evenly spaced points (not exceeding 11 meters) in between the lowest and highest points. Data was collected and samples were taken within 25 cm-by-25 cm quadrats at these points. The exact sampling location was rotated within an area one meter east or down-slope each year of the longer ten-year monitoring study because sampling of aboveground biomass involved removing material.

For this study, plant attributes and physical environmental variables were measured in 1999. Data on plant attributes and chemical environmental variables were collected in 2006. Plant attributes were measured on 2 October 1999 and 19 August 2006 and included maximum stem height (cm), stem density (stems/0.0625 m^2), and aboveground biomass. Average caliber (mm) of five tallest stems was added in 2002.

Physical environmental variables included soil texture, soil moisture, and macro-organic matter (MOM). At each quadrat location, the top ten to fifteen cm of substrate was sampled with a trowel on 2 October 1999. Soil texture was determined using 40 g of substrate and the hydrometer method (Gee and Bauder 1986). Soil moisture was determined by measuring the difference in mass of a 40-g sample before and after being heated at 105^{o}C to constant mass (usually within 24 hours). Macro-organic matter was determined by measuring the mass before and after firing in a muffle furnace at 550^{o}C for 4.5 hours. Elevation was not measured directly. Instead, sampling points were assigned to one of four inundation classes, or zones of elevation, based on years of experience working at the site as the incoming and outgoing tides revealed quadrats with similar relative elevations. Boundaries between inundation classes were based on changes in topography or substrate.

In 2006, sulfide concentration, redox, salinity, and pore water temperature were measured in the substrates at the quadrat locations. Chemical conditions were determined in the pore water of the substrate, where plants have the most sustained and physiologically consequential contact. A modified version of Otte and Morris's (1994) "dialysis vials" were used. At each quadrat, three vials were buried at three corners (two down-slope and the upslope corner farthest way from the transect line). Vials were 22 ml in volume and 9 cm in length. The top of the vial was covered with 41- micron Nitex mesh and secured with a ring screw-top with a hole that exposed the mesh. Vials were filled with deionized water, buried upside down in the substrate and left in the substrate for four to six weeks to equilibrate with the pore water within 5 cm above and below the mouth of the vial. Pink twine and trail flagging were attached to vials to aid in relocating and removing them. Vials were installed starting 19 April and replaced on 20 May, 24 June, 5 August, with final collection of the last set of vials on 3 September. (Each date represents the first day of field work that lasted 3-5 days.) Sulfides were measured for each of these intervals, and salinity and pore water temperature were measured for some of the later intervals.

To measure sulfides, the solution in the vials was subsampled using a syringe, and the subsample was added to a vial of premeasured zinc acetate buffer, which stabilized the samples until they could be processed in the lab. Because the range of sulfide concentrations was not known, multiple subsamples were taken to create fixed samples of multiple dilutions (1:2, 1:10 and 1:100) for processing in the lab. Sulfide samples were analyzed using a colorimetric method described by Cline (1969), which is suitable for natural waters, was developed in anoxic marine basins, and is not affected by salinity or temperature. Standard curves were developed, and the samples were analyzed using a spectrophotometer (Spectral Instruments Model 400 Series).

Salinity (ppt) of the solution in vials was measured with an portable refractometer on 24 June, 5 August, and 3 September. Temperature (^{o}C) of the solution in vials was collected with a pocket thermometer (with metal casing) on the two final dates.

Redox potential (mV) was measured on 5 August using platinum tipped electrodes, a calomel reference electrode, and a portable meter (Cole Palmer Model 5985-80). Five platinum electrodes were arrayed around the quadrat: a center electrode was placed at the lowest corner of the quadrat away from the transect line, and four others were positioned 0.5 m up-slope, down-slope and lateral to the center. Electrodes were inserted to a depth of 10 cm and allowed to equilibrate for at least 30 minutes before readings were recorded. The five readings were averaged for each quadrat, a minimum number recommended for field measurements (Richardson and Vepraskas 2001:94). No correction factor was applied for the purposes of the multivariate analysis because relative redox measurements would remain appreciably the same. For temperatures ranging from 14 to 22 ^{o}C in this study, approximately 252 mV (for cooler temperatures) to 247 mV (for warmer temperatures) would be added to adjust field voltages to redox potentials (Eh's) that would have been measured if a hydrogen electrode had been used as the reference (Richardson and Vepraskas 2001:94-95).

Additional chemical variable data were collected on 17 August 2005. Soil cores were collected at the low edge of the sampling quadrat using a 3-cm wide PVC pipe with a filed (sharpened end) that was pounded to a depth of 15 cm. Samples were stored in a freezer until sent for analysis to AmTest Laboratories in Kirkland, Washington. Salinity was determined using electrical conductivity (SM [Standard Method] 2520B), and pH was also determined using electrical conductivity with temperature compensation (SW-846 9045 [for Soil and Waste]). pH data from this year were used in some regression models containing variables measured in other years. The salinity data were ultimately not used in the models because of the importance of conditions during the early part of the growing season that were captured using the technique implemented in 2006, as described above.

Statistical Analysis

Pearson correlation coefficients were calculated among all environmental variables, among all plant attributes, and among pairs of environmental and plant variables.

Principal components analysis (PCA) was conducted on quadrat samples to simplify variables where possible and inform what was included in the models tested with multiple regression. When both correlation and PCA revealed that percent sand, silt and clay were highly correlated, percent sand alone was used to represent soil texture in subsequent analyses.

For descriptive purposes but not hypothesis testing, simple linear regression was conducted between all plant attributes and environmental variables. ANOVA was conducted on plant attributes in inundation classes and on environmental variables in inundation classes.

A Specified Analysis Plan (SAP) was used for confirmatory statistical analysis with multiple regression. Hypothesized causal relationships among variables were identified before analysis in directed acyclic graphs (DAG), and predictors of interest were then analyzed in the model along with potentially confounding factors (Vittinghoff et al. 2012:410; Zhao, personal communication; Figures 1-5 and 1-6). This approach reduces Type I error (i.e., rejecting the null hypothesis when it is actually true) and permits confirmatory analysis (i.e., hypothesis testing). Exploratory analysis was then conducted based on results of the specified analyses.

Sulfide concentration was collected across the growing season (20 April-3 September), with measurements taken on 21 May, 24 June, 5 August, and 3 September 2006 (Table 1-1). These measurements represented concentrations that had equilibrated with substrate pore water during periods of 4 to 6 weeks. Correlations among sulfide measurements and averages were examined in order to select values for inclusion in multiple regression analyses. Although individual measurements were moderately to strongly correlated, all the averaged values were highly correlated (r≥0.95). (When averages were calculated, individual measurements were not weighted based on the amount of time the vials had remained buried in the substrate.) The average of sulfide concentrations to 5 August was used for the full model because it captured conditions leading up to the date of plant sampling (19 August), including the period of most rapid growth (21 May – 24 June). A model for that period of rapid growth was also tested using fewer environmental variables, i.e., those that were available at that time in the study, and only maximum stem height as the response variable available. The data collected on 3 September were not used because AG biomass had been collected two weeks earlier.

Maximum stem height was measured on 5 and 19 August. Since plant attributes would be expected to respond to past or current rather than future environmental conditions, the September individual measurement and average including September was not considered for inclusion in the multiple regression analyses in the Specified Analysis Plan.

Multiple regression models by design include confounding factors in addition to the predictor of interest. Some factors may not just confound but mediate the effect of others. In other words, a factor has an effect through another factor. To determine that a factor is a mediator of another, several criteria must be met: 1) a "hypothetical causal framework" must exist, i.e., the relationship must make physical, chemical, or biological sense; and 2) "evidence for indirect effect via the mediator is given by a test of the effects of the primary predictor on the mediator, in combination with a second test of the effect of the mediator on the outcome" (Vittinghoff et al. 2012:95). These criteria were considered during interpretation following model testing.

Inundation classes originally designated five elevation zones, but the two highest zones were combined into the Class 4 used in this analysis in order to aggregate enough samples in each category for analysis. As a result, variation was greater in Class 4 than in other classes.

Samples were removed from analyses for several reasons. One % MOM outlier (TN4-E) was removed from the analysis of 1999 physical environmental variables because the value may have resulted from flawed field sampling of substrate and in order to capture the general relationship between % MOM and plant attributes. One quadrat (TN8-D) was removed from some analyses of data from the period of fastest growth (21 May – 24 June) in 2006 because *S. pungens* was not identified at that location until August of that field season. Two quadrats (TS1-D and TS2-D) were removed from PCA and full model testing involving sulfide concentrations, salinity, and pore water temperature because buried vials were empty when retrieved on 5 August. These were at the highest elevation, reached only by the higher high tides, at which *S. pungens* occurred in GHNWR and were >98% sand, a substrate that drains quickly and does not retain moisture. Without surrounding pore water, the solution in the inverted vials drained. Two other quadrats (TN1-D and TN2-A) were removed from PCA analysis and full model testing because vials could not be found in May, probably due to sedimentation during spring storms. Within a few years of the establishment of the transects in 1999, the low end of the *S. pungens* stand eroded in a segment of the north shore of the refuge. As a result, quadrats TN4-A, TN5-A, and TN6-A no plant data was available for 2006 analyses.

In some models, response variables were transformed using natural log in order to improve normal distribution of data and homogeneity of variance.

The R statistical program Version 3.1.1 (2014-07-10) was used for all data analysis (R Core Team 2014). For all tests, alpha levels were set at 0.05. Where appropriate, 95% confident intervals (CI) are reported.

RESULTS

S. pungens and Physical Environmental Variables (1999)

Relationships among Physical Environmental Variables

Soil texture is defined by percentages of particles of different sizes (i.e., sand, silt and clay). Sand was strongly negatively correlated with both silt and clay (r=-0.99 and -0.84, respectively). Smaller particles of the silt and clay fraction were positively but less strongly correlated (r=0.73). The silt portion was considered autocorrelated with the other two portions since it was a function of the two other measured fractions: silt was calculated by subtracting the measured percentages of sand and clay from a total of 100. PCA was used to attempt to reduce these three variables to one that could be used for soil texture in multiple regression. Sand was strongly associated with the first PCA axis (PC1), which explained 90.6% of the variation among samples, and was used for subsequent analyses because it would be easier to interpret in models than PC1 (Figures 1-7 and 1-10, Table 1-2).

A strong negative correlation existed between % moisture and % sand (r=-0.73). Sandy substrates drain quickly and do not hold water (Figure 1-10). A moderately strong positive correlation existed between % moisture and % MOM (r=0.645); this correlation is also evident in the PCA biplot, which shows their association with each other and the first axis (Figures 1-7 and 1-10). Organic matter retains moisture, so substrates with higher % MOM would be expected to also have high % moisture.

Relationships among Plant Attributes

In general, the more stems produced, the greater the biomass. Among plant attributes, stem density and aboveground biomass were strongly positively correlated (r=0.647), while maximum stem height was weakly negatively correlated with stem density (r=-0.224) and weakly positively correlated with AG biomass (r=0.253) (Figure 1-10). Principal components analysis of plant attributes indicated that stem density and AG biomass were strongly associated with each other and the first axis (PC1), which explained 54.9% of variation among quadrats (Figure 1-7). Maximum stem height was strongly associated with PC2, which explained 38.1% of variation among quadrats.

Multiple Regression Models

Simple linear regression between plant attributes and all environmental variables was conducted for descriptive purposes and to aid interpretation (Table 1-4). (See methods section for need to avoid Type I error.) Multiple regression models were designated for confirmatory testing in the Specified Analysis Plan, and followed by examination of exploratory models (Table 1-5). For all plant attributes, the following analysis of physical environmental variables focuses on the model that included % sand, inundation class, % MOM and % moisture. Results for each plant attribute and individual environmental factors are presented below.

Maximum Stem Height and Physical Environmental Variables

Soil Texture

Simple linear regression indicated a negative but not statistically significant association between maximum stem height and % sand (CI: -0.444, 0.192; r^2=0.016;

p=0.428) (Table 1-4, Figure1-10). A stronger association was indicated when the quadratic term was included (R^2=0.091, p=0.059), which may suggest either that tallest stems respond to an optimum level of sand in the substrate and/or the confounding influence of other environmental factors in combination with % sand. Because the first order term of sand was significant in the model used in multiple linear regression (see below), the quadratic term was not added (Zhao, personal communication).

When the effects of other factors were accounted for in the specified model, the effect of % sand was statistically significant. For *S. pungens* with the same inundation, % MOM, and % moisture levels, average maximum stem height increases 0.454 cm (CI: 0.068 cm, 0.840 cm; p=0.023) for each 1% increase of sand in the substrate (Table 1-5). When moisture was removed from the model, the relationship between maximum stem height and sand weakens considerably: average maximum stem height increases 0.147 cm (CI: -0.139 cm, 0.434 cm; p=0.304) for each 1% increase in sand. This change in the effect of % sand (parameter estimate and p-value) indicates that the effect of sand is mediated through moisture (Vittinghoff et al. 2012:95). Designating moisture as a mediator makes sense in the "hypothetical causal framework" (Vittinghoff et al. 2012:95), insofar as sand drains quickly (if the water table is not high) and does not retain much moisture, which negatively affects plant growth. In addition, results of simple regression of the two links in the mediation chain were significant: % sand was negatively associated with % moisture (r^2=0.537, p<0.001); and % moisture was positively associated with maximum height (r^2=0.129, p=0.019).

Inundation Class

Because inundation class was treated as a categorical variable, maximum height in each inundation class was compared to the reference, Class 1. The zone called Class 1 was at the lowest intertidal elevation and experienced the most tidal inundation; Class 4 was at the highest elevation and experienced the least inundation by tides. Class 4 was created from the original two highest zones (4 and 5) so that a sufficient number of data points would be available for analysis. Within the revised Class 4, the three tallest maximum stem heights were found in the original Class 4 and the two shortest stem heights were found in the original Class 5, so the variation in the combined class was greater than for either of the two original classes (Figures 1-7, 1-9 and 1-10).

In general, there is a negative association between maximum stem height and inundation class (Figure 1-9). All classes differed significantly from Class 1, which hosts the tallest stems: maximum stem height decreased by 26.558 cm (CI: -41.534 cm, -11.583 cm; p=0.001) in Class 2, by 17.119 cm (CI: -31.741 cm, -2.497 cm; p=0.023) in Class 3, and by 56.686 cm (CI: -76.050 cm, -37.321 cm; p<0.001) in Class 4 (Table 1-4).

When the effects of other factors were adjusted for in the model, inundation classes remained significantly different and the tallest stems were found in Class 1. For *S. pungens* with the same % sand, % MOM, and % moisture levels, average maximum stem height in Class 2 was 23.518 cm (CI: -38.760 cm, -8.275 cm; p=0.004) shorter than in Class 1 (Table 1-5). For *S. pungens* with the same % sand, % MOM, and % moisture levels, average maximum stem height in Class 3 was 17.311 cm (CI: -31.999 cm, -2.622 cm; p=0.022) shorter than in Class 1. For *S. pungens* with the same % sand, % MOM, and % moisture levels, average maximum stem height in Class 4 was 52.894 cm (CI: -75.579 cm, -30.209 cm; p<0.001) shorter than in Class 1. When moisture was removed from the model, the parameter estimates become slightly more negative but maintain their positions relative to each other and p-values become slightly more significant. Since the effect of moisture was positive, the fact that parameter estimates become more negative when moisture is left out of the model may indicate that the effect of inundation class was mediated by moisture. Moisture differs significantly among inundation classes, with Class 4 at the highest elevation containing about half the moisture of all lower levels ($p<0.001$), and % moisture is significantly positively associated with maximum stem height ($r^2=0.129$, $p=0.019$). Percent moisture therefore satisfies the criteria for a mediator of inundation class outlined by Vittinghoff et al. (2012:95), as described earlier.

Macro-organic Matter

Results of simple regression indicate a positive but weak and not statistically significant association between maximum stem height and % MOM (CI: -0.855 cm, 4.469 cm; $r^2=0.045$; $p=0.178$) (Table 1-4, Figure 10). A stronger and statistically significant association was suggested when the quadratic term is included ($R^2 = 0.1931$, $p=0.006$), which may suggest that the tallest stems were associated with an optimum level of % MOM in the substrate and/or that other environmental factors affect the association with % MOM. One % MOM outlier was removed from this and subsequent analyses because the value may have resulted from flawed field sampling of substrate and in order to capture the general relationship between % MOM and maximum stem height.

When the effects of other factors are accounted for, the association between maximum height and % MOM was negative. For *S. pungens* with the same sand and moisture levels and inundation class, average maximum stem height decreased 2.322 cm

(CI: -5.862 cm, 1.217 cm; p=0.191) for each 1% increase of MOM in the substrate (Table 1-5). So in the full model, % MOM was not significant but the parameter estimate is biologically meaningful and the small sample size in this study may be responsible for the low but not statistically significant p-value (Zhao, personal communication). The quadratic character of the association may also complicate the results of the MLR, which assumes linear relationships though is robust to inclusion of non-linear relationships (Zhao, personal communication). When the quadratic term of % MOM is added to the full model, both the first and second order terms were statistically significant (p=0.057 and 0.027, respectively), but the association between maximum stem height and moisture was weaker (i.e., parameter estimate of moisture decreased by half and was no longer significant). This change suggests that moisture may mediate the effect of % MOM. When moisture was removed from the model and the quadratic of % MOM was kept in, all terms were significant, except for inundation Class 3, which – given the sample size – still has a relatively low p-value of 0.108. The adjusted R^2 was slightly higher (R^2=0.562; p<0.001) for this model (with MOM quadratic, without moisture) than the full model (with moisture and without MOM quadratic) (R^2=0.505; p<0.001). Moisture and % MOM were expected to be closely associated because moisture slows decomposition and increases % MOM, and MOM retains moisture in substrate. Simple regression confirmed this association (r^2=0.416, p<0.001) and, as has already been established, the association between % moisture and maximum stem height was also significant (r^2=0.129, p=0.019) (Table 1-4). The statistical and conceptual criteria for moisture as a mediator of the effect of MOM were therefore met (Vittinghoff et al. 2012:95). This close association is supported by the fact that the model was affected similarly by the inclusion of either % moisture or the quadratic term of % MOM. The quadratic character of the % MOM relationship may be due to confounding effects of other factors, so the model with moisture is preferred for the model, despite the lower R^2 value.

Moisture

Results of simple regression indicate that moisture and maximum stem height were positively associated: maximum stem height increased 0.731 cm (CI: 0.124 cm, 1.337 cm; p=0.019) for each increase of 1% moisture in the substrate (Table 1-4, Figure 1-10).

When other environmental factors were adjusted for, the association with moisture remained positive and statistically significant. For *S. pungens* at the same sand and MOM level and in the same inundation class, maximum stem height increased 1.305 cm (CI: 0.136 cm; 2.474 cm; p=0.030) for each increase of 1% moisture in the substrate (Table 1-5). As described above, moisture was also a mediator for sand, inundation class, and % MOM. The model that included these four factors was statistically significant and explained half the variation in maximum stem height ($R^2=0.505$, $p<0.001$).

Natural-log Transformed Maximum Stem Height

Maximum height was natural-log transformed in an exploratory model with all variables, and the proportion of variation explained in the plant attribute increased ($R^2=0.591$, $p<0.001$) (Table 1-5). In this model, MOM became biologically meaningful if not statistically significant (p=0.074), and all other variables remained significant. The direction (positive or negative) and relative magnitude of all coefficients remained similar to that of the model with untransformed stem height. Inundation class remained the variable with the largest effect on height by an order of magnitude. Percent sand and % moisture were associated with 0.5 and 1.5 percent increases, respectively, in height per unit change of the environmental variable, and % MOM was associated with 3.2 percent decrease in height per unit change in (Vittinghoff et al. 2012:129). Despite the higher R^2 in this model, the focus in this paper has been on results from the models with untransformed data because the parameter coefficients can be interpreted more clearly (Zhao, personal communication).

Stem Density and Physical Environmental Variables

The best specified model for stem density and physical environmental variables included % sand, inundation class, % MOM, and % moisture (R^2=0.531, p<0.001) (Table 1-5). This combination had the highest R^2, explaining more than half the variation in stem density, and all variables – and inundation classes – were statistically significant. Individual environmental variables are considered below.

Soil Texture

Simple regression indicated a statistically significant positive association between stem density and % sand (r^2=0.1743, p=0.006) (Table 1-4, Figure 1-10).

When the effects of other factors were accounted for, the effect of % sand remained positive and statistically significant. For *S. pungens* with the same inundation class and levels of MOM and moisture, stem density increased 1.167 stems/0.0625 m^2 (CI: 0.413 stems/0.0625 m^2, 1.921 stems/0.0625 m^2; p=0.003) for each 1% increase of sand in the substrate (Table 1-5). When moisture was removed from the model, the parameter estimate for % sand drops by two-thirds and is no longer significant (0.35 stems/0.0625 m^2; CI: -0.239 stems/0.0625 m^2, 0.940 stems/0.0625 m^2; p=0.237), which indicates that the effect of sand on stem density is mediated by moisture. As mentioned earlier, the association between sand and moisture was statistically significant (r^2=0.537, p<0.001), and the association between moisture and stem density nearly was (r^2=0.089, p=0.55). The conceptual and statistical criteria were met for moisture as a mediator of the effect of sand on stem density, as was also true for maximum height.

Inundation Class

In general, the association between stem density and inundation class was positive. Inundation class was treated as a categorical variable, and stem density in each class was compared to the reference, Class 1, which was the lowest zone and experiences the most inundation. Simple regression indicated that Classes 3 and 4 differ significantly from Class 1: stem density increased in Class 2 by 17.15 stems/0.0625 m^2 (CI: -14.156 stems/0.0625 m^2, 48.454 stems/0.0625 m^2; p=0.274), in Class 3 by 48.20 stems/0.0625 m^2 (CI: 17.637 stems/0.0625 m^2, 78.768 stems/0.0625 m^2; p=0.003), and in Class 4 by 105.79 stems/0.0625 m^2 (CI: 65.307 stems/0.0625 m^2, 146.265 stems/0.0625 m^2; p<0.001) (Table 1-4, Figure 1-9).

When the effects of other factors were adjusted for in the model, stem densities in all inundation classes were significantly greater than Class 1. For *S. pungens* with the same sand, MOM and moisture levels, stem density in Class 2 was 30.260 stems/0.0625 m^2 (CI: 0.514 stems/0.0625 m^2, 60.006 stems/0.0625 m^2; p=0.046) greater than Class 1 (Table 1-5). For *S. pungens* with the same sand, MOM and moisture levels, stem density in Class 3 was 53.336 stems/0.0625 m^2 (CI: 24.671 stems/0.0625 m^2, 82.001 stems/0.0625 m^2; $p<0.001$) greater than Class 1. For *S. pungens* with the same sand, MOM and moisture levels, stem density in Class 4 was 105.665 stems/0.0625 m^2 (CI: 61.396 stems/0.0625 m^2, 149.934 stems/0.0625 m^2; $p<0.001$) greater than Class 1. When moisture was removed from the model, the parameter estimates drop noticeably, especially in Classes 2 and 4 (23.998 and 87.352 stems/0.0625 m^2, respectively), and only Classes 3 and 4 remained significantly different from Class 1 ($p=0.002$ and $p<0.001$, respectively). This change may indicate that the effect of inundation class was mediated by moisture, as might well be expected across zones experiencing different amounts of tidal inundation. Moisture in at least Class 4 (the highest elevation zone) was statistically significantly different from the others ($p<0.001$), and moisture and stem density were positively associated but not quite statistically significant ($r^2=0.089$, $p=0.055$). The conceptual criterion was met, but the statistical criteria were not fully met (Vittinghoff et al. 2012:95). Nevertheless, moisture appeared to mediate the effect of inundation class, at least in portions of the tidal range.

Macro-organic Matter

Results of simple regression indicate a statistically significant negative association between stem density and % MOM (CI: -10.330 %, 0.092 %; $r^2=0.090$; $p=0.054$) (Table 1-4, Figure 1-10). One outlier was removed from the analysis because the value may have resulted from a flawed methodology (i.e., field sampling of substrate) and in order to capture the general relationship between % MOM and stem density.

When the effects of other factors were accounted for, the association remained negative and statistically significant. For *S. pungens* with the same % sand and % moisture levels and inundation class, stem density decreased by 9.392 stems/0.0625 m^2 (CI: -16.298 stems/0.0625 m^2, -2.485 stems/0.0625 m^2; p=0.009) for each 1% increase of MOM in the substrate (Table 1-5). When moisture was removed from the model, the parameter estimate for MOM moved much closer to 0 and is not significant (β=-1.734; CI: -7.006 stems/0.0625 m^2, 3.536 stems/0.0625 m^2; p=0.509). These changes suggest that the effect of % MOM on stem density is mediated by moisture. As noted earlier, the association between MOM and moisture was statistically significant (r^2=0.416, p<0.001), and the positive association between moisture and stem density was not quite statistically significant (r^2=0.089, p=0.055). The conceptual criterion was met, but the statistical criteria were not quite met (Vittinghoff et al. 2012:95). Nevertheless, given the small sample size, moisture appeared to mediate the effect of MOM.

Moisture

Results of simple regression analysis indicated that stem density and moisture were negatively associated: a decrease in stem density of 1.216 stems/0.0625 m^2 (CI: -2.460 stems/0.0625 m^2, 0.027 stems/0.0625 m^2; r^2=0.089; p=0.055) was associated with an increase of 1% moisture in the substrate (Table 1-4, Figure 1-10). Especially since simple linear regression was conducted for descriptive purposes, this association would be considered biologically meaningful, if not statistically significant.

However, when other environmental factors were adjusted for, the association between stem density and moisture was statistically significant but, notably, positive. For *S. pungens* in the same sand and MOM level and in the same inundation class, stem density increased 3.478 stems/0.0625 m^2 (CI: 1.197 stems/0.0625 m^2, 5.760 stems/0.0625 m^2; p=0.004) for an increase of 1% moisture in the substrate (Table 1-5).

The effect of sand, inundation class, and MOM on stem density were mediated or confounded by moisture, but moisture appears to play a role in the plant's growth through vegetative reproduction beyond that of mediator.

Aboveground Biomass and Physical Environmental Variables

The specified model with % sand, inundation class, % MOM, and % moisture was statistically significant but explained only about a quarter of the variation in AG biomass (R^2=0.262, p=0.009) (Table 1-5). Associations between AG biomass and individual variables were not statistically significant (except for Inundation Class 3 having higher AG biomass than Class 1), though several appeared to be biologically meaningful (Table Table 1-4, Figures 1-9 and 1-10). This peak in Class 3 appeared to shift in 2006 to Class 2 (see discussion section).

Soil Texture

Simple regression indicated a positive association between sand and AG biomass: an increase of 0.092 g AG biomass (CI: -0.078, 0.262; p=0.281) was associated with an increase of 1% sand (Table 1-4, Figure 1-10). The magnitude of the association did not appear to be biologically meaningful.

However, when other environmental variables were adjusted for in the model, AG biomass was found to have a positive and biologically meaningful association with sand: an increase of 0.242 g AG biomass (CI: -0.011, 0.495; p=0.060) was associated with an increase of 1% sand, after adjusting for inundation class, % MOM, and % moisture (Table 1-5). When moisture was removed from this model, the association with sand became smaller and the p-value higher (β=0.108; CI: -0.073, 0.289; p=0.234), which introduced the possibility that the effect of sand on biomass might be mediated by substrate moisture, as was true for maximum stem height and stem density. There is a statistically significant association between sand and moisture (r^2=0.537, p<0.001) but not between moisture and aboveground biomass (r^2<0.001, p=0.951). Moisture did not meet the statistical criteria for being a mediator but remained a confounding factor of the effect of % sand on AG biomass (Vittinghoff et al. 2012:95).

Inundation Class

For descriptive purposes, a simple linear model was tested. Inundation class is a categorical variable, and each class is compared to the reference, Class 1, which is the lowest zone and experiences the most inundation. In general, the association between AG biomass and inundation class was positive, and biomass increases with elevation (Figures 1-9 and 1-10). Class 3 was greater than Class 1 and the difference was statistically significant, while Classes 2 and 4 were also greater than Class 1 but not statistically significantly different: AG biomass in Class 2 is 5.438 g (CI: -4.109 g, 14.985 g; p=0.256) greater than in Class 1, in Class 3 is 18.051 g (CI: 8.730 g, 27.373 g; p<0.001) greater than in Class 1, and in Class 4 is 8.813 g (CI: -3.532 g, 21.158 g; p=0.157) greater than in Class 1 (Table 1-4, Figures 1-9 and 1-10). Although not statistically significant, the drop in biomass in Class 4 relative to Class 3 suggested an overall parabolic relationship between AG biomass and elevation, with the peak at an elevation optimum. This pattern is examined further in the section on analysis of 2006 AG biomass, and a possible shift is considered in the discussion section.

When other environmental variables were adjusted for, the difference with Class 1 increased in Class 2, remains relatively constant in Class 3, and decreased slightly in Class 4. For *S. pungens* with the same sand, MOM and moisture levels, AG biomass in Class 2 was 8.092 g (CI: -1.898 g, 18.082 g; 0.109) greater than Class 1 (Table 1-5). This value was biologically meaningful, and the p-value may have resulted from a small sample size. For *S. pungens* with the same sand, MOM and moisture levels, AG biomass in Class 3 was 18.917 g (CI: 9.290 g, 28.544 g; $p<0.001$) greater than Class 1 (Table 1-5). For *S. pungens* with the same sand, MOM and moisture levels, AG biomass in Class 4 was 7.169 g (CI: -7.699 g, 22.036 g; $p=0.334$) greater than Class 1. When moisture was removed from the model, the parameter estimates drop slightly in Class 2 (7.065 g; $p=0.163$) and more noticeably in Class 4 (4.164 g; $p=0.565$), while the difference between Class 3 and Class 1 remained nearly unchanged. These changes suggested the possibility that the effect of inundation class on aboveground biomass was mediated by moisture, especially at the highest marsh elevations in Class 4. Moisture was statistically significantly different among inundation classes, with the average % moisture in Class 4 being half what it was at lower elevation (23% compared to 44-49%, $p<0.001$). However, as noted earlier, the association between moisture and AG biomass is not significantly different ($r^2<0.001$, $p=0.951$). Moisture therefore did not meet the statistical criteria for being a mediator but remained a confounding factor of the effect of inundation class on AG biomass (Vittinghoff et al. 2012:95).

Macro-organic Matter

Results of simple regression indicated a positive but extremely weak and not statistically significant association between AG biomass and % MOM (β=0.157; CI: -1.304 g, 1.618 g; r^2=0.001; p=0.829) (Table 1-4, Figure 1-10). One outlier was removed from the analysis because the value may have resulted from flawed field sampling of substrate and in order to capture the general relationship between % MOM and AG biomass.

When the effects of other factors were accounted for, the association was negative. For *S. pungens* with the same sand and moisture levels and inundation class, average aboveground biomass decreased 1.507 g (CI: -3.826 g, 0.813; p=0.196) for each 1% increase of MOM in the substrate (Table 1-5). So in the full model, % MOM was not statistically significant, but the parameter estimate was biologically meaningful and the small sample size in this study may be responsible for the low but not statistically significant p-value. Vittinghoff et al. (2012:409) recommended keeping confounding factors in models when p≤0.20. As indicated in the full-model diagram, moist substrates that are rich in organic matter were expected to be low in nutrients, since decomposition is slow and the nutrients are therefore not available to plants (Figure 1-5). When moisture was removed from the model, the estimate of the effect gets much closer to 0 and does not appear to be biologically meaningful (β=-0.25; p=0.756). This change might suggest that moisture mediates the effect of MOM. There was a statistically significant positive association between moisture and MOM (r^2=0.416, p<0.001), but not between moisture and AG biomass (r^2<0.001, p=0.951), as stated earlier. The criteria for moisture as a mediator of the effect of % MOM were not met for AG biomass.

Moisture

AG biomass and moisture were not associated in a biologically meaningful way: an increase in aboveground biomass of 0.011 g (CI: -0.338 g, 0.360 g; R2<0.001; p=0.951) is associated with an increase of 1% moisture in the substrate (Table 1-4, Figure 1-10).

However, when other environmental factors were adjusted for, the association between aboveground biomass and moisture became positive and of greater magnitude. For *S. pungens* in the same sand and MOM level and in the same inundation class, AG biomass increased 0.571 g (CI: -0.195 g, 1.337 g; p=0.139) for each increase of 1% in moisture in the substrate (Table 1-5). This increase was biologically meaningful, and the small sample size may be responsible for the p-value that is low but not statistically significant.

As mentioned in earlier sections, the effect of sand, inundation class, and MOM on aboveground biomass is confounded, but not mediated, by moisture.

S. pungens *and Chemical Environmental Variables (2006)*

Relationships among Environmental Variables

Among the 2006 environmental variables, the strongest correlations involve salinity, redox and temperature (Figure 1-11). Average pore water salinity (21 May – 5 Aug) was negatively and moderately correlated with redox potential (5 August) (r=-0.44) and positively but weakly correlated with pore water temperature (5 August) (r=0.35) (Figure 1-14). Salinity and temperature were expected to be correlated because higher pore water temperatures promote evaporation of water and concentration of salts left behind. In other words, the higher the water temperature, the higher the expected salinity.

Salinity and redox might be expected to be negatively correlated because of the interplay of several factors. Salinity is highest in substrates that a) are primarily influenced by seawater and are farthest from freshwater inputs via groundwater or b) experience inundation but are also exposed long enough for evaporation to concentrate salts. By contrast, the highest redox potentials in the marsh would be expected in substrates that are regularly inundated but drain readily and become aerated due to coarse soil texture (e.g., sandy or gravelly substrates).

These correlations were also evident in the PCA biplot: salinity and redox were both associated with PC1, the axis that explained the greatest amount of variation (28%) among the data points (quadrats). However, salinity had a positive loading on PC1 (0.5874) and redox had a negative loading on PC1 (-0.4710) (Figure 1-11, Table 1-6). A factor loading is the contribution that an environmental variable makes to the component axis, so salinity and redox appear to have opposing effects on PC1. Temperature had a positive loading on PC1 (0.3825), which was a smaller influence than salinity or redox.

Pore water sulfide concentrations were weakly correlated with a number of environmental variables. Sulfide was negatively and weakly correlated with % sand (1999) (r=-0.29), as would be expected since the higher the sand content, the more easily substrate drains and aerates, resulting in a decrease in chemically reduced forms of sulfur and an increase in oxidized forms, especially sulfate (Figure 1-14). Sulfide was positively though weakly correlated with pH (r=0.29), which was surprising given that hydrogen sulfide might be expected to lower pH. However, there were not many high values for sulfide so the correlation direction is determined by a handful of data points, which suggests interaction with other factors. Sulfide was negatively correlated with redox potential (r=-0.25), which would be expected given that sulfur is chemically reduced to forms of sulfide (i.e., H_2S, HS^-, S^{2-}) at low redox potential (Reddy and DeLaune 2008:451-452).

In the PCA biplot, sulfide and pH vectors were nearly identical in direction and magnitude, with loadings on PC2 of -0.4068 and -0.4601, respectively (Figure 1-11, Table 1-6). Unlike the correlation, this similarity suggested a positive relationship once other sources of variation are accounted for. By contrast, % sand had a positive loading on PC2 of 0.4487, and high % sand would be expected to be associated with low sulfide levels and low pH.

Similar results were found for PCA of the environmental variables and stem height growth in June (21 May – 24 June).

Relationships among Plant Attributes

In general, taller stems were thicker and shorter stems were skinnier (see growth-form descriptions in introduction section). Higher AG biomass appeared to result more from an increase in stem density than in stem height, and the denser the stems, the skinnier they were. Maximum plant heights measured on 5 and 19 August 2006 were highly correlated and essentially interchangeable (r=0.99 for both) (Figure 1-13). Maximum stem height (both 5 and 19 August) was moderately correlated with AG biomass (r=0.49 for both). Stem height growth in June (21 May – 24 June) was highly correlated with both measurements of height in August (r=0.87 and 0.86, respectively). Stem density was moderately, though negatively, correlated with stem caliber (r=-0.44) and moderately but positively correlated with AG biomass (r=0.54) (Figures 1-12 and 1-13, Table 1-7).

Average stem caliber (of 5 tallest stems in a quadrat) was moderately strongly and positively correlated with maximum stem height (r=0.65 and 0.64, respectively) and June stem growth (r=0.57). Stem caliber was moderately but negatively correlated with stem density (r=-0.44). AG biomass was positively correlated with all other attributes: it was most strongly correlated with stem density (r=0.54), moderately correlated with maximum stem height (r=0.49 for both dates) and June stem growth (r=0.40), and barely correlated with stem caliber (r=0.07).

Multiple Regression Models

For all plant attributes, the following analysis of chemical environmental variables focuses on the model that included sulfides, salinity, pore water temperature, redox potential and inundation class. Subsequent exploratory analysis was conducted on different models. Results for each plant attribute and individual environmental factors are presented below.

Growth in stem height was measured throughout the study, from April through August 2006. Additional confirmatory and exploratory analysis was conducted for the period of fastest growth from 21 May to 26 June. Fewer variables were measured during that time, so the full model included pore water sulfide concentration, pore water salinity, and inundation class for that period. Exploratory analysis was conducted by adding August measurements of pore water temperature and substrate redox, as well as pH from 2005 and % sand from 1999.

Maximum Stem Height

Sulfide Concentration

Sulfide may be positively associated with sulfide when confounders are factored in, but the period of effect did not appear to be during the period of fastest growth, at least with the variables available for that time. Sulfide concentrations ranged from 6 to 1040 µM through 3 September (and up to 733 µM through 5 August). For the purposes of interpreting results of linear model testing, regression coefficients for sulfides and the corresponding values for the response variable were multiplied by 100. Simple regression did not reveal a statistically significant association: an increase of 100 µM sulfide ions was associated with an increase of 1.9 cm (CI: -6.1 cm, 9.9 cm; p=0.632) in height (Table 1-8, Figure 1-4).

The full model for maximum stem height included sulfide, salinity, pore water temperature, redox potential, and inundation class and was statistically significant, though the model explained a relatively small portion of the variation in stem height (R^2=0.383, p=0.004) (Table 1-9). When the effects of other factors were accounted for in this model, the parameter estimate for sulfide nearly tripled and the p-value dropped considerably: an increase of 5.6 cm (CI: -1.9 cm, 13.2 cm; p=0.142) was associated with an increase of 100 µM in sulfide concentration, after adjusting for salinity, pore water temperature, substrate redox potential, and inundation class (Table 1-9). The increase is biologically meaningful, and the lack of statistical significance may be due to the small sample size. In addition, Vittinghoff et al. (2012:409) recommended keeping variables in models when p≤0.20, especially for small data sets.

When substrate pH (from 2005, the previous year) was added to the model in exploratory analysis, the parameter estimate for sulfide increased and the p-value dropped further: an increase of 6.1 cm (CI: -14.7 cm, 13.7 cm; p=0.109) was associated with an increase of 100 μM in sulfide concentration, after adjusting for salinity, pore water temperature, substrate redox potential, inundation class, and pH (Table 1-9). The change in parameter estimate of over ten percent suggested that pH was a confounder for sulfide concentration (Vittinghoff et al. 2012:409). That oxidation-reduction reactions would be affected by pH was not surprising (Reddy and DeLaune 2008:452). The fact that the pH measurement was from the previous year may indicate some stability of this environmental variable at sampled locations within the marsh. Despite the notable effect on sulfide, the overall model was not much improved with the addition of pH (R^2=0.391, p=0.005).

When models were tested for the period of fastest growth (21 May – 24 June), sulfide and salinity from that period along with inundation class had a statistically significant association with June maximum stem height (R^2=0.330, p=0.003) (Table 1-9). This model explained almost as much variation in stem height as the full model described for the peak of the growing season, but sulfide itself was not statistically significant. The overall model did not improve and sulfide remained not significant when other environmental variables from August were added. Based on the data available for this period, sulfide did not appear to affect June stem height growth, or its effect is confounded by factors that were not measured until August.

Pore Water Salinity

Salinity is consistently negatively associated with maximum stem height. Salinity was averaged over two periods: 21 May - 24 June and 24 June - 5 August. Results of simple regression indicated that average salinity had a negative and statistically significant association with maximum stem height: a decrease of 2.396 cm (CI: -4.720 cm, -0.072 cm) in maximum stem height was associated with an increase of 1 ppt in pore water salinity (R^2=0.129; p=0.044) (Table 1-8 , Figure 1-14).

When the effects of other factors were accounted for, the effect of salinity became greater and more statistically significant: a decrease of 3.177 cm (CI: -5.467 cm, -0.886 cm; p=0.008) in maximum stem height was associated with an increase of 1 ppt in pore water salinity, after adjusting for the effects of sulfide, pore water temperature, substrate redox potential, and inundation class (Table 1-9). When pH (2005) was added to the model, the effect of average salinity dropped to -2.617 cm (CI: -5.103 cm, -0.131 cm) and remained statistically significant (p=0.040). Since the parameter coefficient changed more than ten percent, this exploratory analysis suggested that substrate pH may confound the effect of salinity on maximum stem height, especially considering the fact that pH was measured in the preceding year (Vittinghoff et al. 2012:409).

When models were tested for the period of fastest growth (21 May – 24 June), salinity and sulfide from that period along with inundation class had a statistically significant association with June maximum stem height (R^2=0.330, p=0.003) (Table 1-9). As noted in the section on sulfide, this model explained almost as much variation in stem height as the full model created for the peak of the growing season. Unlike sulfide, salinity was statistically significant in this June model (p=0.044), but the magnitude of the effect was markedly smaller than that seen in the full model: a decrease of 1.18 cm (CI: -2.334 cm, -0.032 cm) was associated with an increase of 1 ppt. The smaller negative effect might be expected since growth during this period was a portion of total height measured at the peak of the growing season. When other environmental variables from August were added, the overall model did not improve but salinity remained a significant factor during this period of rapid growth.

Pore Water Temperature

Results for pore water temperature were not consistent, but the negative effect on stem height appeared to have an impact during the period of rapid growth, and interactions with salinity and inundation were important . Simple regression indicated that pore water temperature measured on 5 August had a negative and statistically significant association with maximum stem height: a decrease of 3.507 cm (CI: -6.632 cm, -0.381 cm) in maximum stem height was associated with an increase of 1 ^{0}C in pore water temperature ($r^2=0.129$; $p=0.029$) (Table 1-8, Figure 1-14).

However, when the effects of other environmental factors were accounted for, the association became smaller and was not statistically significant: a decrease of 1.472 cm (CI: -4.824 cm, 1.880 cm) was associated with an increase of 1 ^{0}C in pore water temperature ($p=0.375$), after adjusting for sulfide concentration, pore water salinity, substrate redox potential, and inundation class (Table 1-9).

Pore water temperature interacts with a number of other environmental factors, which may be mediators or otherwise confound temperature's effect on maximum stem height (Figure 1-6). A second specified model was created with pore water temperature and inundation class in order to determine whether or not sulfide, salinity, redox and 2005 pH were potential mediators of temperature's effect on maximum stem height. In the base model with inundation class, water temperature still had a negative association with stem height: a decrease of 3.084 cm (CI: -6.542 cm, 0.375 cm) was associated with an increase of 1 ^{0}C in pore water temperature (p=0.079) (Table 1-9). Given the small sample size, the association can be considered biologically meaningful. Examination of potential mediators established a link only between pore water temperature and salinity: temperature was associated with salinity (r^2=0.142, p=0.026), and salinity in turn was associated with maximum stem height (r^2=0.106, p=0.044). Higher water temperature would be expected to affect salinity through evaporation, which would concentrate salinity. Conceptual and statistical criteria were thus met for salinity as a mediator of pore water temperature.

When August pore water temperature was added to exploratory models of June stem growth, along with redox and 2005 pH, it was found to improve the specified model that included only sulfide, salinity and inundation class. In the exploratory model, temperature was negatively associated with stem growth: a decrease of 0.928 cm (CI: -2.422 cm, 0.565 cm) was associated with an increase of 1 ^{0}C but was not statistically significant (p=0.213) (Table 1-9). However, Vittinghoff et al. (2012:409) recommended retaining variables with p-values <0.20, especially when data sets are small. The doubling or tripling of parameter coefficients comparing inundation classes 2 and 3 to Class 1 suggested that pore water temperature was a possible confounding factor for inundation class (Figure 1-19). Pore water temperature had a negative and biologically meaningful association with stem growth in June: a decrease of 1.329 cm in stem growth was associated with an increase of 1 ^{0}C (r^2=0.85, p=0.084). In Class 4, the magnitude of difference from Class 1 decreased by about twenty percent, which suggested that temperature may also be a confounding variable in this elevation zone. Higher pore water temperatures would be expected to be associated with inundation classes or elevations that are tidally inundated but then warm up once exposed to air during daytime. Warmer water holds less dissolved oxygen needed for respiration by roots. Pore water temperature in Class 4 was found to be different from other classes to a degree that is biologically meaningful if not statistically significant (p=0.08) (Figure 1-19). The evidence for pore water temperature as a confounding factor of inundation class during the period of rapid growth appears strong.

Substrate Redox Potential

Low redox potential typically indicates oxygen depletion in substrates as well as the increased likelihood of forms of sulfide being present. It would generally be expected to be negatively associated with height, and the results revealed this association once confounding factors were addressed. This factor was measured only on 5 August near the peak of the growing season, and simple regression analysis did not indicate that redox potential was associated with maximum stem height (Table 1-8, Figure 1-14).

However, when the effects of other environmental factors were accounted for, the association was negative and statistically significant: a decrease of 9.3 cm (CI: -17.9 cm, -0.7 cm) in maximum stem height was associated with an increase of 100 mV in redox potential, after adjusting for the effects of sulfide concentration, average pore water salinity, pore water temperature, and inundation class (p=0.035) (Table 1-9). (Redox was measured in mV, and estimates of parameter coefficients and the response variable were multiplied by 100 here in order to improve the clarity of interpretation.)

Although not anticipated at the start of the study and therefore not illustrated in the DAG (Figure 1-6), salinity mediated the effect of redox on maximum stem height. There was a statistically significant association between redox and salinity (r^2=0.156, p=0.013), as well as between salinity and stem height (r^2=0.106, p=0.044). Since salt ions increase the conductivity of water, salinity would be expected to affect the rate of oxidation-reduction reactions. So the conceptual and statistical criteria were met for salinity to be a mediator of the effect of redox on stem height (Vittinghoff et al. 2012:95).

When pH was added to the model, the effect was slightly more negative and statistically significant: a decrease of 9.6 cm (CI: -18.1 cm, -1.0 cm) in maximum stem height is associated with an increase of 100 mV in redox potential, after adjusting for the effects of sulfide concentration, average pore water salinity, pore water temperature, and inundation class (p=0.030) (Table 1-9). This slight change in the parameter coefficient did not meet the ten percent threshold suggested by Vittinghoff et al. (2012:409), and pH was not a statistically significant variable in the model (p=0.257). However, redox and pH are known to interact, the first being a measure of electron activity and the second being a measure of proton activity (Reddy and DeLaune 2008:81). Oxidation-reduction reactions may result in molecular species that increase or decrease pH, and substrate pH may affect the degree to which an oxidation-reduction reaction proceeds in one direction or the other. The conceptual criterion was met for pH as a confounder of redox. The statistical criteria might have been met with a larger sample size.

When August redox was added to exploratory models of June stem growth, along with pore water temperature and pH from 2005, it was found to improve the specified model that included only sulfide, salinity and inundation class. In the exploratory model, redox was negatively and significantly associated with stem growth: a decrease of 5 cm (CI: -9.2 cm, 0.8 cm) was associated with an increase of 100 mV (p=0.022) (Table 1-9). In

Classes 2 and 3, the large increases in parameter coefficients comparing growth to Class 1 suggested that substrate redox may be a confounding factor for inundation class. In Class 4, the magnitude of difference from Class 1 decreased by about twenty percent, strengthened the possibility that substrate redox was a confounding variable for this elevation zone. Lower redox potentials would be expected to be associated with elevations with substrates that remain saturated. Higher redox potential would be expected to be associated with elevations that experience inundation but that drain quickly or experience re-oxygenation from returning tides. Somewhat counterintuitively, redox in Class 1 was on average 100 mV higher than other classes (p=0.06) (Figure 1-19). If oxygen levels were higher at the lowest elevation (presumably due to replenishment by incoming tides), especially in combination with low salinity (see section on Pore Water Salinity), these conditions could contribute to early and faster growth that leads to the tallest stems later in the growing season.

Inundation Class

In general, the association between maximum stem height and inundation class was negative (Figures 1-4 and 1-18). In other words, on the whole, maximum stem height decreased with an increase in elevation. Inundation class was treated as a categorical variable, and each class was compared to the reference, Class 1, which was the lowest elevation zone and experienced the most inundation. Results of simple linear regression, which are presented for descriptive purposes, indicated that all classes were shorter than Class 1 and the difference was statistically significant for Class 4 at the highest elevation but not for Classes 2 and 3: maximum stem height in Class 2 was 12.90 cm (CI: -36.289 cm, 10.481 cm) shorter than in Class 1 (p=0.270); in Class 3 was 11.62 cm (CI: -32.027 cm, 8.797 cm) shorter than in Class 1 (p=0.256); and in Class 4 was 54.95 cm (CI: -82.339 cm, -27.568 cm) shorter than in Class 1 (p<0.001) (Table 1-8, Figure 1-18).

When other environmental variables are adjusted for, the trend between stem height and inundation class remained negative, but the difference from Class 1 doubled in Class 2, increased somewhat in Class 3, and decreased considerably in Class 4. For *S. pungens* with the same sulfide concentrations, average pore water salinity, pore water temperature, and substrate redox potential, maximum stem height in Class 2 was 25.811 cm (CI: -49.682 cm, -1.940 cm) shorter than in Class 1 (p=0.035); in Class 3 was 16.029 cm (CI: -36.442 cm, 4.384 cm) shorter than in Class 1 (p=0.119); and in Class 4 was 36.510 cm (CI: -67.186 cm, -5.834 cm) greater than in Class 1 (p=0.021) (Table 1-9). Although the difference between Class 1 and Class 3 was not statistically significant, the decrease in maximum stem height was biologically meaningful, and the non-significant p-value may be a result of small sample size.

When substrate pH (from 2005, the previous year) was added to the model for exploratory purposes, the difference from Class 1 increased in all classes, especially Class 3, which became nearly statistically significant. For *S. pungens* experiencing the same sulfide concentrations, average pore water salinity, pore water temperature, substrate redox potential, and pH, maximum stem height in Class 2 was 29.031 cm (CI: -53.942 cm, -4.121 cm) shorter than in Class 1 (p=0.024); in Class 3 was 24.346 cm (CI: -49.278 cm, 0.587 cm) shorter than in Class 1 (p=0.057); and in Class 4 was 42.211 cm (CI: -76.836 cm, -7.586 cm) greater than in Class 1 (p=0.015) (Table 1-9). These exploratory results suggested that the effect of inundation class, especially Class 3, on maximum stem height was mediated by substrate pH. When pH was compared across inundation classes using ANOVA, pH in Class 3 was significantly lower than in all other classes (approximately 5.5 compared to 6.5; $p=0.033$) (Figure 1-19), so accounting for this environmental variable improved the model.

In the specified model that included just pore water temperature and inundation class and omitted putative mediators of both, the difference in maximum stem height between Class 2 and Class 1 changed the most compared to the full model and was no longer statistically significant (CI: -39.453 cm, 5.823 cm; $p=0.14$) (Table 1-9). This change between Classes 2 and 1 indicated that the effect of inundation class at the lowest elevations is mediated by another variable. As explained in the section on pore water temperature, examination of potential mediators in the full model established a link only between pore water temperature and salinity: temperature was associated with salinity ($r^2=0.142$, $p=0.026$), and salinity in turn was associated with maximum stem height ($r^2=0.106$, $p=0.044$). ANOVA results for salinity across inundation classes indicated that salinity in Class 1 is lower than that in all other classes, though the difference was not statistically significant (5.7 compared to 8.6-9.8 ppt, $p=0.19$) (Figure 1-19). However, confounding variables with $p<0.20$ may well be important, especially with small data sets (Vittinghoff et al. 2012: 409). By contrast, differences between Classes 3 and 4 and Class 1 in the reduced model remained of magnitude similar to the full model and statistically significant or nearly so. These differences among inundation classes indicated interaction between environmental variables and these elevation zones. In other words, different factors could have an effect or be more important than others at different elevations. In an exploratory step, adding substrate pH to this reduced model resulted in an increase in the difference in stem height between Class 3 and Class 1 and a p-value below 0.05 ($p=0.021$).

The effect of pH was not statistically significant in this exploratory model but may be biologically meaningful given the small sample size: a decrease of -6.549 cm (CI: -15.725 cm, 2.628 cm) in maximum stem height was associated with an increase of 1 unit on the logarithmic pH scale, after adjusting for pore water temperature and inundation class (p=0.155). Underscoring the potential role of pH was the fact that, when pH was compared across inundation classes using ANOVA, Class 3 was statistically significantly lower than all other classes (5.6 compared to 6.5-6.6, p=0.033) (Figure 1-19).

For the period of fastest growth of stems (21 May – 24 June), the association between growth and inundation class was generally negative. In other words, stem growth in June decreases on the whole as elevation increases. Results of linear regression indicated that all classes grew less than Class 1. The difference was statistically significant only for Class 4 at the highest elevation but biological meaningful for the others: stem growth in Class 2 was 8.077 cm (CI: -18.524 cm, 2.370 cm; p=0.0.125) less than in Class 1; in Class 3 was 6.494 cm (CI: -15.801 cm, 2.814 cm; p=0.165) less than in Class 1; and in Class 4 was 25.077 cm (CI: -37.311 cm, -12.842 cm; p<0.001) less than in Class 1 (Table 1-8). These differences were more distinct than maximum height differences measured at the peak of the growing season in August, though the pattern is similar overall.

Specified models focusing on the period of fastest growth of stem height included sulfide, salinity and inundation class, which were the data collected at that time (Table 1-1). Inundation class had statistically significant or biologically meaningful effects on maximum stem height only when variables measured later in the growing season, such as pore water temperature, redox, and pH, were included in the model. The exception was Class 4, in which a decrease of 23.559 cm (CI: -35.488 cm, -11.629 cm) in stem height was found compared to other classes (p<0.001) (Table 1-9). Specified and exploratory models for this period were found to be statistically significant or biologically meaningful, but only explained about half as much variation in stem growth as did models of peak height with a full complement of variables.

Inundation class consistently had a significant effect on maximum stem height. Physical and chemical environmental variables differed across elevation zones. Sand was higher and moisture and MOM were lower in Class 4 compared to other classes (p=0.004, p<0.001, p=0.002, respectively) (Figure 1-19). Pore water temperature was also higher in Class 4 than others (p=0.08). pH was lower in Class 3 than others (p=0.033); sulfides were higher in Class 2 than other classes (p=0.015); redox and salinity were higher in Class 1 than others (p=0.06 and 0.19, respectively). This interaction among variables underscores the limited utility of single-factor analysis and need for multivariate techniques. It also illustrates the complex environment that *S. pungens* must be able to handle.

Percent Sand (1999)

In exploratory analysis, % sand from 1999 was included in some models because it was shown to have a number of mediating and confounding effects on physical variables and had a significant effect in the multi-variate models specified for that first year of this study. Further, based on years of field experience at the site, soil texture was expected to have been relatively consistent over several years, so % sand measured in 1999 was considered to be an adequate surrogate for % sand in 2006.

Results of simple regression with 2006 maximum stem height indicated that there was a weak but statistically significant negative association: a decrease in stem height of

0.398 cm (CI: -0.780 cm, -0.017 cm) was associated with an increase of 1% sand (r^2=0.108, p=0.041) (Table 1-8, Figure 1-14). However, when % sand was added to the 2006 full model used in the MLR, its association with maximum stem height weakened and was not statistically significant: an increase of 0.083 cm (CI: -0.290 cm, 0.456 cm) was associated with an increase of 1% sand (p=0.651) (Table 1-9). The change in significance may reflect the need for contemporaneous data, as well as further exploration of the relationship between physical and chemical variables in this complex environment. Additionally, sand was not a statistically significant factor and did not improve any of the models for stem growth during the period 21 May to 24 June (Table 9-1).

Substrate pH (2005)

Results generally indicated that taller stems were found in more acidic substrate. Lower pH can be attributed to high levels of inundation or saturation, including from landward surface water and groundwater flow: saturation slows decomposition and increases % MOM, and it decreases redox potentials and increases hydrogen sulfide concentrations.

Substrate pH was measured in 2005 soil cores and was expected to be relatively constant from year to year. It was therefore used as a surrogate for pH in 2006. It was expected to have a number of mediating or otherwise confounding relationships with the variables in the specified model. For example, acidity is associated with elevated hydrogen sulfide concentrations, and substrate pH affects and is affected by redox potential (Reddy and DeLaune 2008:81, 451).

Results of simple regression indicated that pH has a negative but very weak and not significant relationship with maximum stem height: a decrease of -4.579 cm (-14.217 cm, 5.060 cm) is associated with an increase of 1 on the pH scale (r^2=0.024, p=0.342) (Table 1-8, Figure 1-14). The coefficient appears relatively small, given that the change of 1 unit in pH is on a logarithmic scale.

When pH (2005) was added in exploratory analysis to the full model based on 2006 data, the association with maximum stem height was negative but not statistically significant: a decrease of 5.491 cm (CI: -14.932 cm, 3.951 cm) in maximum stem height was associated with an increase of 1 on the pH scale (p=0.242) (Table 1-9). As explained in the section about inundation class above, the addition of pH (2005) resulted in an increase in the magnitude of difference between inundation Class 3 and Class 1, and this difference became nearly statistically significant (p=0.057), especially considering the small sample size. This change suggests that there was interaction between pH and inundation class and that, in Class 3, pH had a confounding effect on inundation's relationship with maximum stem height.

During exploratory analysis, when pH (2005) was added to the no-mediators model containing pore water temperature and inundation class, the association between maximum stem height and pH was still negative but increased in magnitude compared to models that contained mediators: a decrease of -6.549 cm (CI: -15.725 cm, 2.628 cm) was associated with an increase of 1 on the pH scale (p=0.155) (Table 1-9).

When pH was added to exploratory models of June stem growth with sulfide, salinity, inundation class, as well as water temperature and redox from the peak of the growing season, the amount of variation in growth explained was similar to the reduced specified model ($R^2=0.322$, $p=0.013$ and $R^2=0.330$, $p=0.003$, respectively), but nearly all variables were statistically significant or biologically meaningful, unlike in the reduced model (Figure 1-9).

Stem Density and Chemical Environmental Variables Plus Inundation

Simple regression did not indicate any significant associations with chemical variables measured in this study, and these results were reflected in the multiple regression analysis (Tables 1-8).

The specified model for stem density and chemical variables (sulfide, salinity, pore water temperature, and redox) also included inundation class because it was a variable known for that year. This full model was not statistically significant ($R^2=0.111$, $p=0.177$), and inundation class was the only variable with a statistically significant or biologically meaningful association with stem density. Inundation class was included because it was known for the year that chemical variables were measured. It is a physical variable with chemical consequences, but what affects stem density was not captured by the variables measured in this study. Class 2 was 55.628 stems/0.0625 m^2 more dense than Class 1 (CI: -4.638, 115.894; $p=0.069$) and Class 4 was 90.462 stems/0.0625 m^2 more dense than Class 4 (CI: 13.017, 167.908; $p=0.024$) (Table 1-9, Figure 1-18).

An exploratory model that was statistically significant and explained more of the variation in stem density included pore water temperature, inundation class, % sand, and pH ($R^2=0.245$, $p=0.027$). This combination of physical and chemical variables explained only about a quarter of the variation in stem density, which is about half the variation explained by the specified model that included all physical variables. Percent sand was the only variable that was statistically significant, with an increase of 0.988 stems/0.0625 m^2 being associated with 1% increase in sand (CI: 0.187, 1.789; p=0.018) (Table 1-9). This association is similar in magnitude and significance to that found for % sand and stem density in the full model for 1999. In that year, the effect of sand was found to be mediated by % moisture, and it is likely that the same link was at work in 2006. Sand increases drainage and therefore aeration of the substrate. *S. pungens* in more aerated substrates typically produced more belowground biomass in general, shorter rhizomes, and therefore more active nodes that produce stems (personal observation, unpublished data).

Stem Caliber and Inundation and Chemical Environmental Variables Plus Inundation

Simple regression conducted for descriptive purposes indicated that there were no statistically significant associations between stem caliber and chemical variables (Table 1-9, Figure 1-16). However, linear regression revealed that there was a statistically significant difference between two classes and Class 1: stem calibers in Class 3 were 1.466 mm smaller than those in Class 1 (p=0.020), and those in Class 4 were 2.747 mm smaller than those in Class 1 (p=0.002) (Table 1-9, Figure 1-18).

The specified model with sulfide, salinity, pore water temperature, redox and inundation class was not statistically significant (R^2=0.093, p=0.210) (Table 1-9). Inundation Class 3 was 1.563 mm smaller than Class 1 (CI: -1.563, 0.740; p=0.04). Pore water temperature was of additional interest since p<0.20 (Vittinghoff et al. 2012:409): stem calibers decreased 0.191 mm for an increase of 1 ^{o}C (CI: -0.441, 0.058; p=0.127). The physical variables in this model appear to have had more potential effect on stem caliber than chemical variables measured in this study. However, physical factors affect the chemical environment. For example, temperature would be expected to affect dissolved oxygen in pore water, which would affect the root environment and the ability of the plant to conduct aerobic respiration. Temperature could also affect evaporation, which could lead to concentration of salts and an increase in salinity.

The exploratory model that included simply pore water temperature and inundation class was nearly statistically significant but explained relatively little of the variation in stem caliber (R^2=0.162, p=0.053). The effect of pore water temperature was of similar magnitude as in the simple regression but was nearly significant (CI: -0.427, 0.005; p=0.055). Class 3 remained significantly different from Class 1: calibers in the higher elevation zone were 1.550 mm smaller than in the lowest zone (CI: -2.806, -0.274; p=0.019) (Table 1-9).

Aboveground Biomass and Inundation and Chemical Environmental Variables Plus Inundation

Simple regression conducted for descriptive purposes did not reveal any statistically significant associations between AG biomass and chemical variables (Table 1-8, Figure 1-17). Similarly, neither the specified models nor the exploratory models were statistically significant, R^2 values were below zero, and no individual variables were significant. In the specified model, salinity was the only variable with R^2<0.20, which is Vittinghoff et al.'s (2012:409) threshold for variables in models of small data sets. A decrease of 1.761 g in AG biomass was associated with an increase of 1 ppt (CI: -4.083, 0.560; p=0.131) (Table 1-9).

Generally, physical variables explained the variation in AG biomass more effectively than the chemical variables measured in this study. Inundation was the only variable assessed in both years. In 2006, AG biomoss in Class 2 was greater than Class 1 and was notable for being the only factor in the analyses conducted for descriptive purposes for which the p-value was <0.20. AG biomass was 13.952 g greater in Class 2 than in Class 1 (CI:-5.537, 33.441; p=0.155) (Table 1-8). Class 3 was similar to Class 1 and Class 4 was the least productive of all the classes. These differences suggest an overall parabolic relationship between AG biomass and elevation, with the peak at an elevation optimum, as was observed in 1999 (Figure 1-9). However, the peak appears to have shifted waterward from Class 3 to Class 2. This pattern and a possible shift is considered in the discussion section.

DISCUSSION

Summary of Environmental Factors Associated with Plant Attributes

Maximum stem height appeared to be responsive to more environmental variables than other attributes. When confounding factors, especially inundation class and moisture, were accounted for, maximum stem height was positively associated with % sand, which increases drainage and aeration of the substrate (except where the water table remains high), which facilitates respiration in roots and overall plant growth. Inundation class, or elevation, which affects depth and frequency of flooding, was negatively associated with maximum stem height. Despite the potentially negative effects of flooding, which include reduced light penetration and gas exchange, stem heights were tallest at lower elevation. This maximum height may be attributable to rapid stem elongation triggered by anoxic conditions and etiolation triggered by low light, as well as lower salinities in the lowest, most regularly flushed zone (see section on tall stems). Some tall portions of *S. pungens* stands in GHNWR were growing in sandy substrate that was also flooded regularly at low elevation, so sand may not play the role of increasing drainage in these areas. Moisture was positively associated with maximum stem height. Water is a requirement for photosynthesis and growth but can also be a stress. *S. pungens* is adapted to saturated conditions through aerenchyma, asexual reproduction, and likely anaerobic respiration. In some places in the marsh, moisture was contributed by overland freshwater inputs, which decreased salinity. When confounding factors were accounted for, MOM was negatively associated with maximum stem height. MOM retains moisture, which can slow decomposition and limit availability of nutrients. MOM also lowers pH, which can affect nutrient availability. Salinity was negatively associated with maximum stem height. It inhibits growth by altering osmoregulation. Stems are tallest in the lowest elevations where salinity was also lowest. However, *S. pungens* is adapted to somewhat saline conditions by using osmoticants to prevent water loss. Redox was negatively associated with maximum stem height. Although low redox levels indicate oxygen depletion, *S. pungens* possesses abundant aerenchyma tissue that enables transport of oxygen from above the ground or water down to the roots and rhizomes, where respiration occurs. When other confounding factors, especially salinity, redox and inundation, were accounted for, sulfide appeared to be positively associated with maximum stem height.

Several measured factors were associated with stem density, though fewer than with stem height. Percent sand, which was used to represent soil texture, was positively associated with stem density. More dense portions of *S. pungens* stands produced more BG biomass. Root and rhizome development may be easier in sandier substrates, which have lower bulk density (Howard 2010). Sandier substrates also drain more readily (except where water tables remain high), and a close relative of *S. pungens* has been shown to produce shorter rhizomes and more dense stems in areas that are less inundated (Ikegami et al. 2007). Inundation class, or elevation, was positively associated with stem density. At higher elevations that experience less inundation, *S. pungens* produced shorter rhizomes, with more active nodes and denser AG stems, which have been shown to characterize the response of congeners to favorable conditions (Ikegami et al. 2007). Moisture was negatively associated with stem density when considered alone but positively associated when confounding factors were accounted for, as was also true for stem height. This change in direction illustrates the importance of including confounding factors in the model and teasing apart some of the effects of moisture, including mediating the effects of other factors. MOM was negatively associated with stem density. It retains moisture that can prevent desiccation, but it can also slow decomposition in saturated substrates, which can cause nutrients to be bound up and not readily available to plants. Organic acids can also contribute to low pH, which can affect nutrient availability. The chemical variables measured in this study did not appear to be associated with stem density.

Stem caliber was only measured during the year that physiochemical variables were measured. Inundation was negatively associated with stem width, most notably in Class 3, which was characterized by low pH. Wider stems are associated with a greater proportion of aerenchyma, which are produced in association with anoxia resulting from inundation (Albert et al. 2013). Largest stem caliber was found at lowest elevation. When confounding factors were accounted for, pore water temperature was possibly negatively associated with stem caliber. Generally, the higher the temperature, the lower the dissolved oxygen. However, there is not a consistent pattern of temperature across the landscape. in some portions of GHNWR, cooler temperatures occur at lower elevations where groundwater may be entering the marsh. In other locations, the cooler temperatures occurred at higher elevation, where afternoon shade mitigated temperatures and or surface water inflow provided a cooling influence.

The physical environmental variables measured in this study explained more variation in AG biomass than the chemical variables. Some of these reflect the correlation between AG biomass and stem density (r=0.65 in 1999 and r=0.54, Figure 1-17). AG biomass was positively associated with % sand when confounding factors were accounted for. Sand improves aeration of substrate, which increases the amount of oxygen reaching the roots and available for respiration. Inundation class was positively associated with this attribute, with the largest amount produced in Class 3 in 1999 and Class 2 in 2006 (see section on AG biomass and the elevation optimum). When confounding factors were accounted for, moisture appeared to be positively associated with AG biomass, so enough water for photosynthesis and osmoregulation has a positive effect. MOM appeared to be negatively associated with biomass production. With respect to chemical variables measured in this study, only salinity appeared to be weakly negatively associated with AG biomass, when confounding factors were accounted for (see section on adaptations to environmental conditions).

Elevation as a Primary but Problematic Variable

Elevation has been identified as a major environmental variable affecting *S. pungens* distribution and attributes (form) in Pacific Northwest tidal marshes (Disraeli and Fonda 1979, Hutchinson 1982, Ewing 1986, Albert et al. 2013). Most directly, elevation affects the frequency and duration of tidal inundation, which is why the current study used inundation classes to designate different elevation zones. However, other factors such as salinity vary as a result of differences in tidal action, though not necessarily in a linear fashion (Burke Watson and Byrne 2009).

Elevation is a problematic variable because it is the most obvious physical gradient in a marsh but does not in and of itself affect plant growth; it can be thought of as a surrogate for other variables that change over the elevation gradient. Further, elevation is associated with ecologically different conditions in the different wetland systems in which *S. pungens* is found. In tidal environments, elevation most directly affects the frequency and duration of inundation (Ewing 1983). In dune environments, another *S. pungens* habitat, elevation affects the distance from the substrate surface to the water table and, after precipitation events, the depth of submergence in the lowest part of the dune slack (i.e., interdunal depression) (Seliskar 1990). In lake fringe environments, yet another *S. pungens* habitat, elevation affects the depth of submergence in standing water, which may vary seasonally but is otherwise not fluctuating daily (Albert et al. 2013). Despite this variety and the problematic nature of this variable, elevation provides an important starting point for exploring factors that affect variation in *S. pungens*, especially because it is unlikely that all important and interacting variables can be measured.

Plant Variation Explained by Different Conditions in Inundation Classes

In the Grays Harbor study, elevation was not measured directly, but inundation classes, or zones, were identified based on years of field observations of incoming and receding tides across the site. (The water's edge hits points of similar elevation at the same time.) The inundation classes indicate relative elevation, with an emphasis on the primary physical condition that varies over elevation.

Inundation classes provide a useful structure for taking a closer look at plant responses to multiple environmental dimensions across the landscape. A summary description of differences in environmental variables in inundation classes along the elevation gradient based on the results of ANOVA's follows: At the lowest elevation, Class 1 was characterized by low salinity (5.68 ppt vs. 8.62-9.8 ppt, p=0.190) and high redox (-165.8 mV vs. -248.0 - -275.9, p=0.063) relative to the other inundation classes. Class 2 was characterized by higher sulfide concentrations (241 μM vs. 91-105 μM, p=0.015), and Class 3 was characterized by lower pH (5.56 vs 6.50-6.66, p=0.033) than other classes. In the highest zone, Class 4 was characterized by higher % sand (90.9% vs. 45.3-56.4%, p=0.004), lower moisture (23.0% vs. 44.4-49.4%, p<0.001), lower MOM (2.0% vs. 6.1-7.9%, p=0.002), and higher temperatures (21.5 ^{o}C vs. 17.2-18.6 ^{o}C, p=0.087) than the other classes. These environmental conditions are depicted in a summary diagram along with *S. pungens* attributes (Figure 1-20).

In this study, inundation class, or relative elevation, was found to affect stem height, stem density, and stem caliber in single-factor ANOVA's (used for descriptive purposes) and in models with multiple physical and chemical variables (used for confirmatory analysis). Although inundation class was analyzed as a categorical variable, trends in plant attribute changes can be described. In general, stem height decreased with decreasing inundation (or with increasing elevation); and stem caliber decreased with decreasing inundation (or increasing elevation) (Figures 1-9, 1-10, 1-14, 1-16, 1-18, 1-20; Table 1-4, 1-8). In 1999, stem density increased with decreasing inundation (or increasing elevation), but the trend became less obvious in 2006 (Figure 1-15 in addition to those above). In 1999 and 2006, a peak in AG biomass was seen in the middle elevations levels, with a shift waterward in the second year (Figure 1-17 in addition to those above). These shifts and other patterns are discussed in the sections below.

Tall Stems at Low Elevation

Generally, taller sweetgrass stems were found at lower elevations, i.e., the zones that were most frequently inundated (Figure 1-20). In 2006, the first height measurements were taken on 20 April, and stems were tallest at that early data in the lowest elevation zone (personal observation). Stems either started growing earlier in the season than those at higher elevations or were growing at a faster rate once started. This observed pattern may be explained in a variety of ways.

Rapid stem elongation has been found to occur in several species of *Schoenoplectus* and *Bolboschoenus* (formerly members of *Scirpus*) under anoxic conditions(Cronk and Fennessey 2001:96). This phenomenon has been observed in non-tidal wetlands that are constantly flooded, but it is consistent with the earlier and faster stem growth observed at lowest elevations experiencing the most inundation in *S. pungens* stands in GHNWR. The response to anoxia is a physiological adaptation that enables the stems to attain a height that extends above the water surface and reach oxygen that can be transported down to the submerged roots (Cronk and Fennessey 2001:96). The speed of the elongation ensures that sufficient growth occurs before winter energy reserves are depleted in the rhizomes. The rapid growth may be a result of elevated glycolysis rates in the presence of abundant carbohydrate reserves. Redox measured in August was higher in Inundation Class 1 than at other levels, so the elongation response might be expected to apply to all zones rather than distinguishing the lowest from higher zones. Daytime tidal patterns are different during spring months, and redox may not vary across inundation classes in the same way during the period of most rapid growth.

Another factor influencing stem height during the growing season may be reduced light under flooded conditions. In a greenhouse study, Ikegami et al. (2008) found that *Schoenoplectus americanus* stems grew taller and produced more photosynthetic surface area in shaded conditions. In the field, reduced light conditions can be created by tidal inundation or trees near the upland border of the marsh or by tidal inundation

(Karagatzides et al. 2003, Ikegami et al. 2008). Both sources of shading occurred at GHNWR and, in either case, etiolation could result in taller stems (Ikegami et al. 2008).

Alternatively, tidal flooding may have served as a buffer to cooler temperatures in early spring by keeping substrates in low zones warmer than those experiencing more exposure. A likely explanation for earlier or faster growth at low elevation may be that salinity levels were lowest in this zone (Figures 1-19 and 1-20). Salinity interferes with uptake of water, potassium, and CO_2, all of which are required for growth (Cronk and Fennessey 2001:79). Water potential is altered, sodium is preferentially taken up, and CO_2 uptake is limited due to stomatal closure that occurs as a means of preventing water loss in saline conditions. Lower salinity would therefore favor faster growth. The combination of higher redox and lower salinity may explain the taller stems in Inundation Class 1.

Thicker Stems at Low Elevation

Stems at lower elevations were not only taller but also thicker, or more robust, in *S. pungens* stands in Grays Harbor (Figure 1-20). The species produces aerenchyma wherever it growths, but aerenchyma occupy a greater proportion of stem cross-section when roots and rhizomes are waterlogged. In Delaware dune slacks, more aerenchyma was associated with shorter *S. pungens* stems in non-tidal waterlogged areas (Seliskar 1988, 1990). In Lake Michigan, *S. pungens* stems in permanently flooded areas were taller and wider, with greater production of aerenchyma (Albert et al. 2013). In the Tillamook estuarine marsh, taller and wider stems were found at lower elevations (Albert et al. 2013). In the Skagit (Washington) tidal marsh, thicker stems with more enlarged aerenchyma cells were found in anoxic pannes (depressions), which typically remain flooded at low tide

(Ewing 1986). In Grays Harbor, the larger width (caliber) was associated with more inundation at lower elevations, as well as the production of aerenchyma in response to low oxygen conditions. In addition, salinity was lower at lower elevations because of the tidal inundation, or flushing, that prevented concentrations from building up. (Salt can become concentrated in areas inundated by the tide and then exposed to air, which allows evaporation of water but not salt ions.) Salinity has been shown to be negatively associated with stem height (Figure 1-14, Table 1-8). Average redox (-165.8 mV) was also relatively higher at the lowest inundation class, which indicates relatively higher oxygen levels that may result from regular re-oxygenation by tides or by groundwater infiltration (Figure 1-19).

Stem Density Reflects Belowground Response to Elevation

Stem density increased with increasing elevation, or decreasing inundation, most dramatically in 1999. Stems originate from nodes along underground rhizomes, so the response of belowground (BG) structures is revealing (Figure 1-1). Although BG biomass was not a focus of this study, it was collected for each quadrat in the first two years of the study, which permitted close examination of belowground structures including active nodes at which stems originate along rhizomes. Belowground tissue of the higher-elevation plants was characterized by shorter internodes along rhizomes, and more roots and rhizome tissue was found closer to the ground surface, whereas *S. pungens* growing at lower elevation were characterized by longer internodes and less dense roots and rhizomes (personal observation). These morphological differences over the elevation gradient were similar to those described by Albert et al. (2013) in Lake Michigan and

Tillamook Bay. Those researchers noted that the longer rhizomes were associated with "early colonization of habitat" and shorter rhizomes were associated with "denser, older beds," but they did not describe a mechanism for the different plant response (Albert et al. 2013:454). In garden experiments conducted to determine the response of *Schoenoplectus americanus* (formerly *Scirpus olneyi*) to resource availability, Ikegami et al. (2007) found that short rhizomes were produced in more favorable treatments (i.e., sufficient nutrients, relatively low salinity, full sunlight) and long rhizomes were produced in less favorable treatments (i.e., low nutrients, relatively high salinity, low light). Short rhizomes allow the plant to occupy and consolidate ramets in favorable conditions, whereas long rhizomes allow escape from unfavorable conditions or exploration of new areas.

In 1999, stem density increased with decreasing inundation (or increasing elevation); but by 2006, median stem density in Classes 1 and 2 had doubled, while Classes 3 and 4 remained similar to 1999. Since *S. pungens* stem density generally increases with elevation, the shift at the lowest elevations suggests sedimentation and a rising "floor" of the marsh. The changes in stem densities affected AG biomass, as discussed further in the following section on AG biomass.

Aboveground Biomass and Elevation Optimum

Aboveground biomass was not affected in a linear way by elevation. In 1999, aboveground biomass at permanent quadrats increased with decreasing inundation (or with increasing elevation), except that at the upper edge of the stands biomass dropped to levels similar to Class 2. This pattern changed by 2006, with median biomass increasing overall in each class but especially in Classes 1 and 2 in association with the increase in stem density.

The pattern in both year of peaks at middle elevation suggests an optimum elevation or amount of inundation for *S. pungens* (Tables 1-4 and 1-8, Figure 1-20). Although use of inundation classes rather than precisely measured elevation precludes the use of regression analysis, the pattern of aboveground production – with a peak in Class 3 in 1999 – suggests a parabolic relationship between aboveground biomass and elevation (or inundation) (Figures 1-9 and 1-18). A quadratic relationship between aboveground biomass and flooding duration was found in *Schoenoplectus americanus* mesocosms set up in Chesapeake Bay, despite the relatively small tidal range (25 cm) that was tested compared to the natural stands in Grays Harbor that span at least 1 meter in elevation (Kirwan and Guntenspergen 2015). By contrast, in 2006, AG biomass of *S. pungens* in Grays Harbor was not significantly different among classes, which appeared to be a result of the doubling of stem density and corresponding near-doubling of AG biomass at lower elevations in Classes 1 and 2, an increase that brought AG biomass closer to the levels of Classes 3 and 4. Despite the lack of statistically significant difference in AG biomass among inundation classes, a parabolic pattern remained, with the "hump" shifting waterward.

At least two factors may explain this shift. Sediment may be accreting in the lower marsh in the basin, which increases elevation and decreases inundation, possibly creating more favorable conditions for growth within an existing stand. Putative basin-wide accretion is evident in the recent appearance of small plant species such as *Spergularia* on formerly unvegetated mud- and sandflats (personal observation). Another possibility is that freshwater inputs, either through groundwater inputs or overland surface flow, have change salinity. Elevation and salinity interact in that *S. pungens* can grow at lower elevations when salinity is lower; when salinity is higher, the species tolerates less inundation and is found at higher elevation (Ewing 1986). In this study, salinity was only measured in one year, so additional data is needed to determine if there has been a change in salinity. The changes may be localized rather than class- or zone-wide. During a ten-year monitoring study conducted until 2008, specific locations where at least stem heights were found to increase included TN3-A and –B in Class 1, TN7-B in Class 2, and TN8-C and –D in Class 3.

The elevation optimum that results in a AG biomass graph with a "hump" has been observed with *Schoenoplectus* species under experimental conditions. Kirwan and Guntenspergen (2012, 2015) found this optimum in mesocosms that were composed of containers of *S. americanus* arrayed along an elevation gradient in a brackish estuary on the Eastern Shore of the Chesapeake Bay. The adjacent native marsh occurred at the elevation of the optimum identified in the mesocosms, so it does not appear that a "hump" in biomass production was found over the elevation gradient in that naturally occurring marsh. However, the idea of an optimum plant response along any environmental gradient is consistent with both the community and continuum models of plant distribution (Keddy 2007:498). Schile et al. (2014) found a parabolic relationship between biomass and elevation on a community-wide basis in a San Francisco Bay estuarine marsh that included *S. americanus* and *S. acutus*.

Most marsh biomass production occurs just below the mean high tide line (Mitsch and Gosselink 2015:280). This generalization was based on work conducted in a *Spartina* marsh in South Carolina but appears to apply to GHNWR. Maximum *S. pungens* AG biomass occurred below mean high water (MHW), which in Aberdeen is 2.87 m (9.41 ft) above mean lower low water (National Ocean Service). Based on field work coordinated with known tide levels, MHW is slightly below the upper limit of *S. pungens* in GHNWR.

In the Skagit River delta system, AG productivity did not vary in a consistent way along the elevation gradient, but biomass increased many fold at the lowest elevations at which the species dominated (Ewing 1986). This trend reflected transitions from mixed communities or patches to monotypic stands without competition. Transects in the Skagit study were 500-750 m long and extended through the full marsh, with sampling stations more than 100 m apart, whereas transects in GHNWR were placed within *S. pungens* stands with quadrats close enough (≤11 m intervals) to capture patterns at finer resolution. By contrast, on the Fraser River delta AG biomass was greater at higher elevation, which experienced less inundation (Karagatzides and Hutchinson 1991). Salinity, sulfide, and pH were similar but soil texture was sandier in the high marsh (88 vs. 72%), which would be expected to improve drainage. The negative effects of inundation are described in more detail in the section on ecological limits.

Adaptations to Environmental Conditions

Although accretion of sediment may indicate the need to reexamine the inundation classes created for analysis (or challenge the assumption of static classes), the consistency of AG biomass production across all but the highest inundation class in 2006 may also suggest that the species is adapted to handle a range of conditions across the elevation range it occupies. These adaptations are expected since the elevation range represents several dimensions of the plant's ecological range and is accompanied by variation in salinity, soil texture, redox potential, etc., any one of which could prove a stressor. As demonstrated in the Skagit River delta and in Tillamook Bay estuary, *S. pungens* produces aerenchyma, which enable the species to transfer oxygen to roots in saturated substrate and counteract waterlogged conditions and low redox (Ewing 1986, Albert et al. 2013).

In GHNWR, salinity was negatively though weakly associated with maximum stem height but not associated with other plant attributes, even when confounding factors were accounted for. The lack of effect on stem density and AG biomass suggests that the species is adapted to handle salinity. *S. pungens* in James Bay, Canada, was shown to produce osmoticants that aid osmoregulation and prevent water loss in saline conditions (Ewing et al. 1989). In the Skagit marsh, Ewing (1986) also found that AG biomass productivity of *S. pungens* remained consistent along a salinity gradient: as salinity increased, a decrease in shoot size was counteracted by increase in density. Although not consistently linear trends, a similar pattern was observed in GHNWR.

S. pungens is one of many clonal species that make up intertidal marsh communities. The ability to share resources, including the products of photosynthesis, enables a clonal species to expand and to handle environmental stresses (Pennings and Callaway 2000). In GHNWR, *S. pungens* stems in quadrats positioned just upslope from the waterward edge of the stand are often slightly shorter than stems in the middle of the stands. Expansion requires energy and resources from other ramets in the clone, so stems may be shorter as they rely on aid from established ramets. On the other hand, shorter stems may indicate that the plant has reached its ecological limits. In a controlled experiment on the coast of Georgia, Pennings and Callaway (2000) found that a number of salt marsh species depend on clonal integration for expansion into unutilized habitats and saline pannes. The low edge of *S. pungens* stands in GHNWR are expanding into “unutilized” unvegetated mudflats, though at some point it is reaching its ecological limit; and the species regularly spreads into pannes from surrounding stands. So a clonal habit is an adaptation that enables *S. pungens* to meet multiple needs in the tidal environment. A number of researchers have asserted that clonal growth enables *S. americanus* (Maryland) and *S. pungens* (Fraser River) to be successful in patchy environments and that plasticity in above- and belowground structures is an adaptive trait that allows the species to exploit favorable conditions, escape unfavorable conditions, and continually explore local conditions (Karagatzides et al. 2003; Ikegami et al. 2007, 2008, 2009). However, Poor et al. (2005) found in a garden experiment that *S. americanus* (misidentified as *S. pungens*) did not benefit from clonal integration for more than one year in a heterogenous environment and that independent ramets responded to their local environments when producing new ramets. De Kroon and Hutchings (1995;150) suggested that clonal plants are able to acquire resources in an environment ”with a more stable patch structure” than would be found in a system receiving nutrients in “unpredictable pulses.” In other words, species that are clonal and plastic may be best able to colonize and survive in the multi-dimensional marsh mosaic.

The multiple environmental conditions considered in the current study leave little doubt that *S. pungens* handles heterogeneity at several scales in GHNWR, but the mechanisms require more research.

Tidal salt marsh species appear to have several ways of dealing with high sulfide levels, as mentioned below in the section on sulfides. Sulfide levels in *S. pungens* stands at GHNWR do not reach levels that have been found to inhibit growth in other studies. In fact, when confounding factors were accounted for, sulfide was positively associated with stem height. However, there are locally higher sulfide concentrations, especially later in the growing season that were not used in this analysis, that *S. pungens* may be able to handle with a detoxifying mechanism such as leaking oxygen from roots, an internal sulfur-oxidizing enzyme, or an association with sulfur-oxidizing bacteria (Cronk and Fennessey 2001:114). Sulfide is discussed further in a section below.

Ecological Limits of S. pungens Distribution

On the low edge of the stand, *S. pungens* grows to the ecological limit created by physiochemical conditions. With greater inundation comes decreased light availability (Cronk and Fennessey 2001:82). Waves in these dynamic environments increase reflectance and further decrease light that reaches photosynthesizing stems, while dissolved inorganic and organic compounds and particulate matter scatter and absorb more light. Karagatzides and Hutchinson (1991:473) proposed additional effects of inundation: "Inundation . . . by turbid estuarine water . . . may also subject the plants to thermal shock, modify the temperature regime and nutrient mobilization in the substrate, inhibit oxygen diffusion to roots in an anoxic substrate, and leave a patina of fine sediment on shoots and leaves, thereby further reducing growth potential." In subsequent work, Karagatzides et al. (2003:217) asserted that *S. pungens* ramets, which are less dense at low elevations, have reduced resources compared to those at high elevations and therefore "require larger neighborhoods for resource acquisition." (A clear contrast between low and high marsh "neighborhoods" could not be established, in part because environments were so heterogeneous, or patchy on a small scale.) In marine environments, nitrogen has been shown to be more limited as distance from shore increases (Cronk and Fennessey

2001:80). As the species occupying the foreshore, *S. pungens* might also reach its ecological limits due to this chemical factor.

At the upper edge of *S. pungens* stands in GHNWR, the ecological limit appeared to be due to physiochemical or biological factors. At the high end of several transects, some reduction in stem density, and therefore aboveground biomass, was due to the presence of other species. *Distichlis spicata, Juncus balticus, Carex lyngbyei*, *Potentilla anserina* ssp. *pacifica*, *Deschampsia cespitosa,* and *Triglochin maritima* became more abundant. At other locations, *Salix hookeriana* extended out over the marsh at the rate of up to 1 meter per year and shaded the emergent species, which eventually disappeared beneath the canopy. Competition represents a biological factor that creates an ecological limit. Substrates at the very highest quadrats on the south shore of GHNWR consisted of nearly pure sand and were infrequently inundated, which led to very dry conditions. The upper ecological limit here was caused by physiochemical factors, though this portion of the established stand was effectively being buried by sand.

In the Nooksack River delta, Disraeli and Fonda (1979) documented an abrupt transition from *S. pungens*-dominated (formerly *Scirpus americanus*) marsh to *Carex lyngbyei*-dominated but more diverse marsh. The ecotone appeared to coincide with the mean high tide line, indicating the importance of inundation as a driving factor. Ewing et al. (1989:527) suggested that the "sharp ecotone" that characterizes the upper boundary of *S. pungens* (formerly *Scirpus americanus*) stands growing along river channels was evidence that competition with other species creates the upper ecological limit. Additionally, the dominance of *S. pungens* in regularly inundated and anoxic substrates in the Skagit marsh indicates the absence of the biological stress of competition in that zone.

This model of ecological limits is consistent with the idea that zonation results from a plant's tolerance of factors at the "harsh" lower end of the physiochemical gradient and exclusion by competitive species at the "benign" higher end of the gradient (Pennings and Callaway 1992:689). In that study of two salt marsh species, *Salicornia virginica* and *Arthrocnemum subterminalis*, "field patterns are determined by at least two physical factors [i.e., salinity and waterlogging] operating in a complex combination with interspecific competition" (Pennings and Callaway 1992:689-690). In addition to the respective low and high zones of each species, the greatest biomass production for both occurred adjacent to the pronounced border, where the two physical factors were present at moderate levels. In manipulated experiments with congeners *Schoenoplectus americanus* (mid- and high-marsh species) and *S. acutus* (low marsh species), Schile et al. (2017) also demonstrated that ecological limits are created through the interactions between abiotic stress factors, specifically inundation and salinity, as well as biotic interactions between species. Competition reduced growth especially at higher elevations but did not display the "abrupt border" found by Pennings and Callaway (1992:681) in the field.

Comparison to Role of Elevation in Other Marshes

In the Skagit River estuarine marsh, Ewing (1983) found that community composition was affected by salinity, then soil texture, redox and elevation, so other factors can be more important than elevation. (However, elevation can be associated with such factors as soil texture, which can be affected by exposure to wave energy, and redox, which can be affected by regular inundation or exposure to air and drainage during low tide.) Ewing (1983, 1986) found that *S. pungens* dominated low elevations and in areas with moderate to high salinity and soil textures that were sandy or with a moderate amount of clay, and that it was most abundant at the outer edge (seaward side) of the marsh. An increase in stem density down the elevation gradient appears to have been a function of increasing abundance of *S. pungens* as species diversity decreased and monotypic stands occupied the lowest elevations in the marsh (Ewing 1986). Aboveground productivity did not vary in a consistent way along the elevation gradient, except that the biomass increased many fold at the lowest elevations where the species dominated (Ewing 1986).

Elevation affected growth of *S. pungens* in dune slacks (i.e., interdunal depressions) in Delaware (Seliskar 1990) and the permanently flooded fringes of the Lake Michigan (Albert et al. 2013). But elevation factors into the picture in slightly different ways in these two environments. The lake environment was more similar to the tidal marsh environment than was the dune slack environment. In the dune slacks, elevation affected the distance above the water table, which fluctuated with precipitation events. In the Lake Michigan, elevation affected the depth of inundation in permanently flooded shallows or lake fringes. *S. pungens* exhibited different growth forms at different elevations in both settings but not in a consistent way. The growth forms of dune slack populations are affected by elevation in a way that is different from those in intertidal and lake fringe environments. At lowest elevation in the interdunal slacks, sustained waterlogging (in response to water tables raised by precipitation events) inhibited growth, so stems were shorter than at higher, drier elevations in the dunes.

In contrast to the dune populations, the taller stems found at lower elevations in the intertidal areas of Grays Harbor may result from different conditions characteristic of dynamic intertidal areas. The soil surface is exposed for a portion of each day, which allows for re-oxygenation of substrates to some depth. Sandier substrates drain and become aerated – and even in areas that remain saturated due to the high water table, daily tides regularly bring in oxygenated water. An additional difference in the tidal environment may be salinity, which was not mentioned as a factor in the dune slacks. Regular flushing by tides keeps salinity at lower elevations relatively low compared to some higher elevations. (Landscape setting can affect how much overland freshwater flow is experienced at higher elevations in tidal marshes.) Ewing (1986) found larger stems (by biomass) in less saline anoxic pannes along transects located closer to freshwater inputs from the Skagit River.

In the deepest and mid-elevation permanently flooded portion of the Great Lakes, *S. pungens* was up to three times as tall as at the short stems found at the upper, drier elevations (Albert et al. 2013). These authors also found that stem height was inversely related to elevation in the tidal marshes of Tillamook Bay estuary in Oregon.

Salinity

When chemical variables were analyzed, pore water salinity had the heaviest loading on and was positively correlated with the first PCA axis (Figure 1-11, Table 1-2). It was negatively associated with maximum stem height and stem growth during the period of rapid growth (21May – 24 June). It appeared to be negatively associated with AG biomass, when other confounding factors were accounted for, and was the only environmental variable in the full model that had a p-value below 0.40 (p=0.13, Table 1-9). Stem height and AG biomass are moderately correlated (r=0.49), which strengthens the argument for the effect of salinity on biomass (Figure 1-13).

In GHNWR, *S. pungens* occupies areas with salinity that ranges from 0-18 ppt from 20 April to 5 September. This range is also reflected in published studies. Ewing (1986) found that salinity was negatively associated with shoot investment and leaf area of *S. pungens* (formerly *Scirpus americanus*) in the Skagit marsh, as was found in GHNWR, but that there was no negative trend in AG biomass. In a greenhouse study using plants from James Bay, Ewing et al. (1989) found that growth of *S. pungens* (formerly *Scirpus americanus*) was negatively affected at 5 ppt and that death occurred at 10 ppt. Average pore water salinity in GHNWR stands fell in between these values. Earlier field work in James Bay found salinity ranging from 0 to 10 ppt, with *S. pungens* occupying low salinity areas along river banks that were inundated daily by freshwater tides (Ewing and Kershaw 1986). Karagatzides and Hutchinson (1991) found *S. pungens* (formerly *Scirpus americanus*) occupied portions of the Fraser River delta marsh with lower-salinity (5-6 ppt) compared to those areas dominated by *Bolboschoenus maritimus* (formerly *Scirpus maritimus*) (10.5-13 ppt). In a greenhouse study, Howard (2010) found that salinity of 18 practical salinity units (psu, equivalent to 18 ppt) affected growth of *Schoenoplectus californicus* and *Bolboschoenus robustus* (misidentified as *Schoenoplectus robustus*). Salinity levels in *S. pungens* stands in GHNWR were generally below 18 ppt but reached that maximum during July and August at the waterward edge of some transects. So the species appears to be able to withstand those levels at least later in the growing season.

As discussed in the section on adaptations above, species that grow in saline habitats are adapted to handle salinity. Ewing et al. (1989) found that *S. pungens* (formerly *Scirpus americanus*) in James Bay was salt-sensitive but limited the effects of salinity by accumulating glycine betaine as an osmoticant that helps prevent water loss.

Salinity and moisture interact in a consequential way. Moisture is positively associated with maximum stem height and AG biomass, whereas salinity is negatively associated with these attributes. Moisture facilitates plant growth, but the degree to which that water carries salinity with it determines the net or integrated effect of these two variables on maximum height and AG biomass.

Soil Texture

In the current study, soil texture was determined by measuring percent sand, silt and clay particles, but only sand was used in the models because silt and clay were highly correlated and all three particles were associated with the primary axis in the PCA (Figure 1-7, Table 1-2). Generally, the higher the sand content, the faster substrate would be expected to drain as tides recede, so redox would be expected to be higher except where high water tables keep substrate saturated. A larger portion of the largest particle size could also indicate zones of higher energy along the shoreline. On the southern shore of GHNWR, which is exposed to westerly winds, the substrate is nearly 100% sand at the highest elevation. (Since the sand would not hold water, the liquid in the buried vials drained out a number of times, which resulted in missing data for two quadrats.) This shoreline at the western end of the manmade airport strip was the site of deposition of dredged material, which is primarily sand, in the 1970's (Smith et al. 1976:57) (see Chapter 3).

In simple regression analysis conducted for descriptive purposes, sand was found to have a statistically significant positive association only with *S. pungens* stem density, though the association was weak. When the quadratic term was added to the model, the association of sand with maximum stem height was nearly statically significant. This model may indicate that *S. pungens* is tallest at an ecological optimum characterized by an intermediate level of sand (see Figure 1-10 in which smoother line may suggest optimum range). Disraeli and Fonda (1979) found that substrates of *S. pungens* stands on the Nooksack River delta were high in sand content, though poorly draining due to the high water table. In the Fraser River delta, Hutchinson (1982) found that *S. pungens* formed monotypic stands on well-drained silty-sand substrates and that seaward expansion of these sands occurred in the lee of "megaripples," which provided a lot of sand but also some protection from wave energy. In the Skagit River delta, Ewing (1983) found that *S. pungens* grew most often on sand, where redox was higher than in clayey substrates. However, in later work, Ewing (1986) found an interaction between soil texture and salinity: soil texture was correlated with productivity of *S. pungens* only in areas of lower salinity (≤4 ppt) with relatively small portions of sand (9-21%). These results suggest that factors other than soil texture have greater effect on the growth of *S. pungens* in this delta system. In the dune systems of the Delaware coast, *S. pungens* grows in the slacks between dunes, where it is subject to sand deposition during storm events (Seliskar 1990). Sand accretion appeared to stimulate stem growth. In a greenhouse experiment, stems buried by 10-20 cm of sand twice during several months grew taller than those not buried. Although the *S. pungens* stands in GHNWR are able to withstand burial, stem density dropped and stem height decreased in the high portions of the south shore where sand accumulated over ten years. In the Tillamook marsh of coastal Oregon, *S. pungens* was found in a range of substrates from coarse gravels to dense clays (Albert et al. 2013). In coarse sands and gravels, *S. pungens* produced fine roots and rhizomes, which is consistent with the belowground growth pattern of Grays Harbor stands at higher, better draining elevations. In a greenhouse experiment conducted with species native to marshes in the northern Gulf of Mexico, where sandy substrates are not common, *Schoenoplectus californicus* demonstrated variable (i.e., not consistent) response to clay, silt and organic substrates (Howard 2010).

Sulfides

Sulfide concentration was a focus of this study because of its potential dual role – i.e., stimulant and inhibitor – in plant growth, because of inconsistent results from other studies, and because of the limited data for Pacific Northwest marshes. The best model tested with multiple regression included sulfide, salinity, pore water temperature, redox and inundation class. Of these variables, only sulfide had a positive association with maximum stem height when confounding factors were accounted for. It was not a statistically significant association ($p=0.1420$), but Vittinghoff (2012:409) recommends keeping variables in the model when $p<0.20$. When pH was added to the model for an exploratory trial, the p-value dropped to 0.102, which would be in the realm of biologically meaningful associations. So sulfides deserve more attention.

Generally, average sulfide levels for the period 20 April to 5 August were low in the *S. pungens* stands in GHNWR. Most were below 100 µM, and the highest was 530 µM. Among inundation classes, the highest average was 241 µM in Class 2, which is more than twice as high as all other classes. This class was also characterized by finer texture substrate (55% fines compared to 10-45% in other classes), but did not have the lowest redox or pH. Class 2 was also where AG biomass was greatest in the year that sulfide was measured, though there was not a statistically significant association between AG biomass and sulfide in the full model.

The hypothesis that low elevations would have the lowest sulfides was not supported by these results. They contrast with Karagatzides and Hutchinson's (1991) findings that sulfides were lower at low elevations of *S. pungens* than at high elevations in the Fraser River delta. However, all values at GHNWR were well below the 1mM (1,000 μM) level that Bradley and Dunn (1989) found to be negatively associated with height and biomass of *Spartina alterniflora* and that Koch and Mendelssohn (1989) demonstrated to negatively affect root biomass in *S. alterniflora.* Sulfide concentrations in *S. pungens* stands were at or above the levels (2.9-67.93 μM) that Ewing et al. (1997) found to be negatively correlated with shoot elongation in brackish *S. patens* marshes of coastal Louisiana. Similarly, GHNWR sulfide levels were above 10 μM, which Pezeshki et al. (1991) found negatively affected carbon assimilation in *S. patens* under controlled redox and pH conditions. However, it should be noted that the method used in Grays Harbor measured all sulfide species (H_2S, HS^- and $S^{2-)}$) in pore water, whereas the controlled study measured H_2S only. In a greenhouse study focused on soil type and salinity, Howard (2010) found that sulfide levels of 2.33-19.99 μM (0.07-0.60 ppm) did not affect growth of *Schoenoplectus californicus* and *Bolboschoenus robustus* (misidentified as *Schoenoplectus robustus*), but nearly all values in GHNWR were higher than this range.

Tidal salt marsh species are adapted to detoxify sulfide in a number of ways, including leaking oxygen from roots to the surrounding environment, release of volatile sulfur compounds (e.g., hydrogen sulfide, dimethylfulfide, dimethyl disulfide), and oxidation of sulfide within the roots tips via enzymatic or bacterial action (Cronk and

Fennessey 2001:113-114). One or more adaptations may explain why sulfide is weakly associated with stem height only; however, more work is needed on detoxifying mechanisms and specifically on *S. pungens*.

In summary, the sulfide levels in the *S. pungens* stands at GHNWR were relatively low but appeared to be positively associated with stem height and possibly AG biomass. High levels of sulfide do not appear to develop because these stands were at the lowest elevation of the marsh, were generally washed by the tides at least once a day, and were not characterized by the tide channel banks and back marsh topography that typified the classic work on short and tall forms of *Spartina* (Reddy and DeLaune 2008:473).

Applying Lessons to Future Work

Future work on *S. pungens* at GHNWR would benefit from a number of improvements to field and analytical methods. First, all environmental variables should be measured during the same growing season, rather than in different years, so that correlations and associations can be identified with more precision. A period of special interest would be earlier in the growing season, especially during the period of most rapid growth (May-June). Elevation should be measured directly so that it can be analyzed in multiple techniques as a continuous variable, rather than as a categorical variable based on the researcher's observation and experience. In addition, repeated measurements of redox and pH, which can vary more quickly than other variables, would strengthen a study. Season averages would be more representative of conditions experienced by growing plants, and repeated measures techniques could be used for analysis of differences among sampling sites or zones. All variables could be standardized in multiple regression analysis so that their relative importance is not affected by the units of measurement. (PCA does standardize variables.)

A larger sample size would increase the power of all statistical tests. A particularly interesting approach that would then become possible is structural equation modeling (SEM), which is a multivariate analysis technique for testing "complex hypotheses involving multiple pathways" (McCune and Grace 2002:234, Grace 2006). In "recognition that we are rarely able to measure with absolute accuracy the underlying properties of conceptual interest," SEM incorporates both indicator variables that are measured and latent variables that are not measured (McCune and Grace 2002:242). For some analyses in the current study, the sample size was as low as 34 and as high as 43, which proved too small for SEM (Tear, personal communication; Zhao, personal communication). A minimum of 50 samples quadrats would be required to conduct SEM, and 20 quadrats per variable in the model would be ideal (McCune and Grace 2002).

Implications and Future Research

Environmental factors that affect the growth and characteristics of the ecologically and culturally significant species *S. pungens* include inundation, salinity, soil texture, redox and sulfide concentration. The species displays a great deal of plasticity across the landscape and complex environmental gradients. Maximum stem height is the most responsive attribute, and AG biomass is the least, which indicates a high level of adaptation to these tidal systems. The analysis underscores the necessity of anticipating interactions among these factors. These results are of use to land managers, Native American tribes, restoration ecologists, and environmental planners and suggest a number of new questions.

As Native American weavers worry about the decline of this species (see Chapters 2 and 3), it will remain important to understand the environmental conditions that favor growth forms desired by weavers, i.e., taller and more supple stems with high length to width ratio. Albert et al. (2013) employed a method to measure mechanical strength of stems in the context of ecosystem services. This method might be used to characterize suppleness of *S. pungens* stems. Albert et al. (2013) found that thinner stems with less aerenchyma were more flexible. At GHNWR, the most supple stems were found in upper portions of the marsh that were shaded at least part of the day (personal observation).

S. pungens AG biomass, driven by stem density, is increasing in major portions of GHNWR. What has caused peak AG biomass to shift to a lower inundation class? Either the elevation optimum has shifted due to changes in other factors, or sediment accretion is occurring and the “floor” of the basin is rising. If, for instance, freshwater input has increased and is lowering salinity, *S. pungens* would be able to withstand more inundation and grow at lower elevation (Ewing 1986). On the other hand, if elevation is changing due to sediment accretion, increased *S. pungens* growth is responding in a manner typical of the way it grows at higher elevation (i.e., greater stem density). Over time, stem characteristics may change. At some sampling locations, stem height has already been observed to have decreased, mirroring an observation that gave rise to weavers’ worries about the population. On a landscape level, there are basin- or bay-wide processes, such as sedimentation, that should be tracked; but there are also upland factors, such as forest clearing for development or addition of impervious surfaces, that can affect the timing and volume of freshwater inputs. Human communities count on coastal marshes for wave attenuation and sediment retention (Albert et al. 2013). What ecosystem services may be affected by changes in the marsh? And what do changes in the GHNWR marsh mean for the estuary as a whole?

A species native to the estuarine marshes of the Pacific Northwest, *S. pungens* is of interest to restorationists. Small projects on the Duwamish River and major projects in the Nisqually River delta and the Skokomish River delta are among the projects in Washington and Oregon that have included the species (personal observation; Harwell 2015; Dublanica, personal communication). The Nisqually and Skokomish tribes are principals or partners in a number of these projects. Unfortunately, these efforts have had only limited success thus far, possibly because conditions in which *S. pungens* is most competitive are not well understood or perhaps because the watersheds that hosted stands historically have been highly altered (see Chapter 3). The Cowlitz plan to incorporate the species in an estuarine project on the Columbia River because of its cultural significance (Stout, personal communication). Recently, experimental floating wetlands that include *S. pungens* were set up on the Duwamish with the goals of improving fish habitat and providing a supply of this culturally important plant (Bowles, personal communication). Improving our understanding of the ecology of *S. pungens* in our regional systems increases the likelihood of successful outcomes.

As with all coastal marsh species, growth of S. pungens must be considered in the context of climate change (Kirwan and Guntenspergen 2012, 2015). How will the species respond, not just to sea-level rise but also to elevated CO_2? Is it already responding? How resilient is it? Schile et al. (2014) modeled tidal marsh distribution in response to sea-level rise and focused on the roles of vegetation, sediment and upland habitat. These authors found that brackish marshes with highly productive species, such as members of *Schoenoplectus*, were likely to experience less elevation loss than less productive marshes typical of higher salinity. This resilience is a function of maintaining elevation relative to sea level by accumulating mineral sediment and organic matter produced by the plants themselves. *S. pungens* would appear to be among the resilient species, but can we predict more accurately how it might fare? Using mesocosms that manipulated elevation to simulate sea-level rise, Schile et al. (2017) determined that *S. americanus* and *S. acutus* responded to both the increased physiochemical stress of inundation and the biological stress of competition. In the face of sea-level rise, will the forces that determine ecological limits of *S. pungens* change? Does the plasticity of *S. pungens* make it "more likely to survive novel environmental conditions" (Gratini 2014:11)? Finally, how might constraints on inland migration posed by natural and manmade barriers in Bowerman Basin affect its fate?

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Table 1-1. Sampling schedule for plant attributes and environmental variables measured at quadrats along 10 transects in *Schoenoplectus pungens* stands in Grays Harbor National Wildlife Refuge, Washington. pH was combined with 2006 variables in principal components analysis and multiple regression models. Multiple dates for environmental variables in 2006 correspond to dates that buried vials were removed from the substrate after 4-6 weeks. Measurements collected on 3 Sep 2006 were not used in statistical analysis because the period of burial included some time after the collection of aboveground biomass.

		1999	**2005**	**2006**				
VARIABLES	**UNITS**	**2 Oct**	**17 Aug**	**21 May**	**24 Jun**	**5 Aug**	**19 Aug**	**3 Sep**
Plant Attributes								
Maximum stem height	cm	X		X	X	X	X	X
Stem density	no. stems/0.0625 m^2	X					X	
Aboveground biomass	g (dry)	X					X	
Stem caliber	mm, ave of 5 tallest stems in quadrat						X	
Environmental Variables								
Inundation class	zone assigned	X		X	X	X	X	
Soil texture	% sand, % silt, %clay	X						
Moisture	% mass	X						
Macro-organic matter	% mass	X						
pH	[unitless]		X					
Sulfides	µM			X	X	X		X
Salinity	ppt				X	X		X
Pore water temperature	^{o}C					X		X
Redox potential	mV					X		

Table 1-2. PCA rotation matrix and importance of components for 1999 environmental variables. One quadrat (TN4-E) was omitted because % MOM was an outlier, possibly due to error in methodology. See biplot in Figure 1-7.

```
Rotation:
                 PC1     PC2     PC3     PC4     PC5     PC6
sand.2Oct99  -0.4675  0.0435 -0.3827 -0.1327  0.1676 -0.7664
silt.2Oct99   0.4458 -0.0190  0.4353  0.4298 -0.2238 -0.6137
clay.2Oct99   0.4428 -0.1124  0.1399 -0.8569  0.0381 -0.1896
moist.2Oct99  0.4574  0.2118 -0.2509  0.2036  0.8010 -0.0018
mom.2Oct99    0.3409  0.5340 -0.5781 -0.0112 -0.5141  0.0006
inun.class   -0.2476  0.8094  0.4973 -0.1477  0.1206  0.0005

Importance of components:
                          PC1    PC2    PC3    PC4    PC5    PC6
Standard deviation     1.9981 0.9147 0.8996 0.5094 0.3198 0.0018
Proportion of Variance 0.6654 0.1394 0.1349 0.0432 0.0171 0.0000
Cumulative Proportion  0.6654 0.8048 0.9397 0.9830 1.0000 1.0000
```

Table 1-3. PCA rotation matrix and importance of components for 1999 plant attributes. All quadrats were included in this analysis. See biplot in Figure 1-8.

```
Rotation:
                   PC1     PC2     PC3
maxht.cm.2Oct99 0.0361 -0.9190  0.3927
stdens.2Oct99   0.7000  0.3037  0.6464
agmass.g.2Oct99 0.7133 -0.2516 -0.6542

Importance of components:
                          PC1    PC2    PC3
Standard deviation     1.2835 1.0693 0.4574
Proportion of Variance 0.5491 0.3811 0.0697
Cumulative Proportion  0.5491 0.9303 1.0000
```

Table 1-4. Results of simple linear regression analysis of 1999 *Schoenoplectus pungens* plant attributes (maximum stem height, stem density, and aboveground biomass) on environmental factors (sand, inundation class, macro-organic matter (MOM), and moisture) in 1999. Inundation class is treated as a categorical factor, and classes are compared to the reference (class 1), which is the zone found at the lowest tidal elevation. These regressions were conducted for the purpose of descriptive analysis and were not specified models tested in the Specified Analysis Plan. Models tested for the purpose of additional exploratory analysis are italicized. An asterisk (*) marks $p<0.05$; a dot (.) marks $p<0.10$. N=43.

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	r^2 or Adjusted R^2	p-value
Maximum stem height (cm)					
v. % sand	-0.126	0.157	-0.444, 0.192	0.016	0.428
v. % sand + % sand^2				0.091	0.059.
% sand	1.765	0.828	0.090, 3.439		0.005*
% sand^2	-0.017	0.007	-0.031, -0.002		0.026*
v. inundation				0.461	<0.001*
class 2	-26.558	7.398	-41.534, -11.583		<0.001*
class 3	-17.119	7.223	-31.741, -2.497		0.023*
class 4	-56.686	9.566	-76.050, -37.321		<0.001*
v. % MOM	1.807	1.317	-0.855, 4.469	0.045	0.178
v. % MOM + MOM^2				0.193	0.006*
% MOM	15.314	4.536	6.140, 24.489		0.002*
% MOM^2	-0.949	0.308	-1.571, -0.327		0.004*
v. % moisture	0.731	0.300	0.124, 1.337	0.129	0.019*
Stem Density (stems/0.0625 m^2)					
v. % sand	0.840	0.289	0.256, 1.424	0.1743	0.006*
v. inundation				0.414	<0.001*
class 2	17.15	15.46	-14.156, 48.454		0.274
class 3	48.20	15.10	17.637, 78.768		0.003*
class 4	105.79	20.00	65.307, 146.265		<0.001*
v. % MOM	-5.119	2.578	-10.330, 0.092	0.090	0.054.
v. % MOM + MOM^2				0.106	0.043*
% MOM	-20.378	9.576	-39.748, -1.009		0.040*
% MOM^2	1.072	0.649	-0.241, 2.385		0.107
v. % moisture	-1.216	0.615	-2.460, 0.027	0.089	0.055.
Aboveground Biomass (g)					
v. % sand	0.092	0.084	-0.078, 0.262	0.023	0.281
v. inundation				0.239	0.004*
class 2	5.438	4.716	-4.109, 14.985		0.256
class 3	18.051	4.605	8.730, 27.373		<0.001*
class 4	8.813	6.098	-3.532, 21.158		0.157
v. % MOM	0.157	0.723	-1.304, 1.618	0.001	0.829
v. % moisture	0.011	0.173	-0.338, 0.360	<0.001	0.951

Table 1-5. Results of multiple linear regression (MLR) of 1999 *Schoenoplectus pungens* plant attributes (maximum stem height, stem density, and aboveground biomass) on environmental factors (sand, inundation class, macro-organic matter (MOM), and moisture) in 1999. Inundation class is treated as a categorical factor, and classes are compared to the reference (class 1), which is the zone found at the lowest tidal elevation. Models were tested as part of a Specified Analysis Plan, which reduces the risk of Type I error and allows confirmatory interpretation of results. Models tested for the purpose of additional exploratory analysis are italicized; p-values are provided but prone to Type I error. Exploratory analysis includes natural log (ln) transformation of some response variables. An asterisk (*) marks $p<0.05$; a dot (.) marks $p<0.10$. N=43.

Plant Attribute v. Environmental Factor	**Coefficient Estimate (β)**	**Standard Error**	**95% Confidence Interval**	**Adjusted R^2**	**p-value**
Maximum stem height (cm)					
v. % sand + inun class + % MOM + % moisture				0.505	<0.001*
% sand	0.454	0.190	0.068, 0.840		0.023*
Inun class 2	-23.518	7.508	-38.760, -8.275		0.004*
Inun class 3	-17.311	7.235	-31.999, -2.622		0.022*
Inun class 4	-52.894	11.174	-75.579, -30.209		<0.001*
% MOM	-2.322	1.743	-5.862, 1.217		0.191
% moisture	1.305	0.576	0.136, 2.474		0.030*
v. % sand + inun class + % MOM				0.448	<0.001*
% sand	0.147	0141	-0.139, 0.434		0.304
Inun class 2	-25.867	7.852	-41.792, -9.942		0.002*
Inun class 3	-17.856	7.636	-33.341, -2.370		0.025*
Inun class 4	-59.765	11.356	-82.796, -36.734		<0.001*
% MOM	0.551	1.264	-2.012, 3.113		0.666
v. % sand + inun class + % MOM + MOM^2 + % moisture				0.560	<0.001*
% sand	0.571	0.186	0.192, 0.950		0.004*
Inun class 2	-24.361	7.088	-38.765, -9.957		0.002*
Inun class 3	-12.436	7.138	-26.941, 2.069		0.090.
Inun class 4	-40.865	11.741	-64.727, -17.004		0.001*
% MOM	15.484	7.850	-0.470, 31.437		0.057.
% MOM^2	-1.012	0.436	-1.899, -0.125		0.027*
% moisture	-0.575	0.628	-0.701, 1.850		0.366
v. % sand + inun class + % MOM + MOM^2				0.562	<0.001*
% sand	0.494	0.166	0.157, 0.830		0.005*
Inun class 2	-25.302	6.997	-39.506, -11.098		<0.001*
Inun class 3	-11.650	7.069	-26.001, 2.701		0.108
Inun class 4	-40.747	11.714	-64.527, -16.967		0.001*
% MOM	19.956	6.130	7.511, 32.401		0.003*
% MOM^2	-1.213	0.377	-1.977, -0.448		0.003*

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	Adjusted R^2	p-value
Ln(Maximum stem height)					
v. % sand + inun class + % MOM + % moisture				0.591	<0.001*
% sand	0.005	0.002	0.001, 0.009		0.014*
Inun class 2	-0.221	0.074	-0.371, -0.071		0.005*
Inun class 3	-0.158	0.071	-0.303, -0.014		0.033*
Inun class 4	-0.621	0.110	-0.844, -0.398		<0.001*
% MOM	-0.032	0.017	-0.066, 0.003		0.074.
% moisture	0.015	0.006	0.004, 0.027		0.010*
Stem Density (stems/0.0625 m^2)					
v. % sand + inun class + % MOM + % moisture				0.531	<0.001*
% sand	1.167	0.372	0.413, 1.921		0.003*
Inun class 2	30.260	14.653	0.514, 60.006		0.046*
Inun class 3	53.336	14.120	24.671, 82.001		<0.001*
Inun class 4	105.665	21.807	61.396, 149.934		<0.001*
% MOM	-9.392	3.402	-16.298, -2.485		0.009*
% moisture	3.478	1.124	1.197, 5.760		0.004*
v. % sand + inun class + % MOM				0.419	<0.001*
% sand	0.350	0.291	-0.240, 0.940		0.237
Inun class 2	23.998	16.149	-8.754, 56.750		0.146
Inun class 3	51.883	15.704	20.035, 83.733		<0.001*
Inun class 4	87.352	23.356	39.984, 134.721		<0.002*
% MOM	-1.735	2.599	-7.006, 3.536		0.509
v. % sand + inun class + % MOM + MOM^2				0.499	<0.001*
% sand	0.949	0.355	0.228, 1.669		0.011*
Inun class 2	24.975	15.001	-5.479, 55.429		0.105
Inun class 3	62.616	15.157	31.845, 93.386		<0.001*
Inun class 4	120.243	25.115	69.258, 171.229		<0.001*
% MOM	31.826	13.144	5.143, 58.510		0.021*
% MOM^2	-2.097	0.807	-3.736, -0.458		0.014*

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	Adjusted R^2	p-value
Aboveground Biomass (g)					
v. % sand + inun class + % MOM + % moisture				0.262	0.009*
% sand	0.242	0.125	-0.011, 0.495		0.060.
Inun class 2	8.092	4.921	-1.898, 18.082		0.109
Inun class 3	18.917	4.742	9.290, 28.544		<0.001*
Inun class 4	7.169	7.324	-7.699, 22.036		0.334
% MOM	-1.507	1.143	-3.826, 0.813		0.196
% moisture	0.571	0.377	-0.195, 1.337		0.139
v. % sand + inun class + % MOM				0.236	0.011*
% sand	0.108	0.089	-0.073, 0.289		0.234
Inun class 2	7.065	4.960	-2.995, 17.125		0.163
Inun class 3	18.678	4.823	8.896, 28.461		<0.001*
Inun class 4	4.164	7.174	-10.385, 18.713		0.565
% MOM	-0.250	0.798	-1.869, 1.369		0.756

Table 1-6. PCA rotation matrix and importance of components for 2006 environmental variables. Four quadrats (TN1-D, TN2-A, TS1-D and TS2-D) were omitted because vials were either not found or were found empty at the time of at least one measurement. See biplot in Figure 1-11.

Rotation:

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
S2.ave.to5Aug06	0.3466	-0.4068	0.2984	-0.2985	-0.7231	0.0567	-0.1015
sal.ave.to5Aug06	0.5874	0.0558	-0.0324	0.2325	0.2533	0.5229	-0.5091
temp.5Aug06	0.3825	0.0163	-0.5197	0.5485	-0.3207	-0.3896	0.1669
redox.5Aug06	-0.4710	-0.1810	-0.3392	0.2612	-0.3328	0.6650	0.0952
sand.2Oct99	-0.0373	0.4487	-0.5567	-0.5581	-0.2222	-0.0296	-0.3543
pH.16Aug05	0.2991	-0.4601	-0.4136	-0.4157	0.3505	0.1487	0.4583
inun.class	0.2755	0.6208	0.2090	-0.0594	-0.1648	0.3260	0.5984

Importance of components:

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.4072	1.2634	1.0860	0.8838	0.7808	0.7507	0.5384
Proportion of Variance	0.2829	0.2280	0.1685	0.1116	0.0871	0.0805	0.0414
Cumulative Proportion	0.2829	0.5109	0.6794	0.7910	0.8781	0.9586	1.0000

Table 1-7. PCA rotation matrix and importance of components for 2006 plant attributes, including stem caliber which was not measured in 1999. All quadrats were included in this analysis. See biplot in Figure 1-12.

Rotation:

	PC1	PC2	PC3	PC4
maxht.cm.19Aug06	-0.6594	0.1854	-0.5170	-0.5133
stdens.19Aug06	-0.1279	-0.7276	0.4231	-0.5247
stcalib.mm.19Aug06	-0.4998	0.4601	0.7302	0.0727
AGmass.g.19Aug06	-0.5469	-0.4740	-0.1429	0.6752

Importance of components:

	PC1	PC2	PC3	PC4
Standard deviation	1.377	1.288	0.572	0.343
Proportion of Variance	0.474	0.415	0.082	0.029
Cumulative Proportion	0.474	0.889	0.971	1.000

Table 1-8. Results of simple linear regression analysis of 2006 *Schoenoplectus pungens* plant attributes (maximum stem height, stem height growth (21 May – 24 Jun), stem density, average stem caliber, aboveground biomass) on environmental factors (average pore water sulfide (20 Apr – 5 Aug) and June sulfide (21 May – 24 Jun), substrate redox potential (5 Aug), average pore water salinity (21 May – 5 Aug), pore water temp (5 Aug), and inundation class in 2006, with additional testing of substrate texture (% sand, 1999) and pH (2005). Inundation class is treated as a categorical factor, and classes are compared to the reference (class 1), which is the zone found at the lowest tidal elevation. These regressions were conducted for the purpose of descriptive analysis and were not specified models tested in the Specified Analysis Plan. Models tested for the purpose of additional exploratory analysis are italicized. An asterisk (*) marks p<0.05; a dot (.) marks those <0.10. Sample sizes differed due to variation in field methods and resulting missing data: average sulfide, n=34; June sulfide, n= 37; salinity, n=35; pore water temperature, n=38; redox, n=39; % sand, n=39; pH, n=39. Multiple regressions were conducted with the sample size of the variable with the smallest n.

Plant Attribute v. Environmental Factor	**Coefficient Estimate (β)**	**Standard Error**	**95% Confidence Interval**	**r^2**	**p-value**
Maximum stem height (cm)					
v. average sulfide	0.019	0.040	-0.061, 0.099	0.007	0.632
v. average salinity	-2.396	1.147	-4.720, -0.072	0.106	0.044*
v. pore water temp	-3.507	1.539	-6.632, -0.381	0.129	0.029*
v. substrate redox pot	-0.040	0.049	-0.139, 0.059	0.018	0.421
v. inundation				0.266	0.003*
class 2	-12.90	11.52	-36.289, 10.481		0.270
class 3	-11.62	10.05	-32.027, 8.797		0.256
class 4	-54.95	13.49	-82.339, -27.568		<0.001*
v. % sand ('99)	-0.398	0.188	-0.780, -0.017	0.108	0.041*
v. substrate pH ('05)	-4.579	4.757	-14.217, 5.060	0.024	0.342
Stem height growth in June (cm)					
v. sulfide (Jun)	0.002	0.010	-0.019, 0.024	0.001	0.828
v. salinity (Jun)	-1.383	0.634	-2.668, -0.098	0.112	0.036*
v. pore water temp(Aug)	-1.329	0.747	-2.848, 0.190	0.085	0.084.
v. substrate redox (Aug)	-0.008	0.023	-0.055, 0.038	0.004	0.715
v. inundation				0.281	0.003*
class 2	-8.077	5.141	-18.524, 2.370		0.125
class 3	-6.494	4.580	-15.801, 2.814		0.165
class 4	-25.077	6.020	-37.311, -12.842		<0.001*
v. % sand ('99)	-0.133	0.089	-0.312, 0.047	0.059	0.143
v. substrate pH ('05)	-2.927	2.117	-7.220, 1.367	0.050	0.175

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	r^2	p-value
Stem Density (stems/0.0625 m^2)					
v. average sulfide	-0.018	0.083	-0.186, 0.150	0.001	0.826
v. average salinity	0.761	2.308	-3.916, 5.438	0.003	0.743
v. pore water temp	4.721	3.502	-2.389, 11.831	0.049	0.186
v. substrate redox	-0.043	0.094	-0.234, 0.147	0.006	0.648
v. inundation				0.023	0.289
class 2	41.84	25.32	-9.573, 93.246		0.107
class 3	14.69	22.10	-30.181, 59.566		0.511
class 4	44.66	29.66	-15.543,104.866		0.141
v. % sand	0.621	0.366	-0.121, 1.363	0.072	0.098.
v. substrate pH	9.992	9.032	-8.307, 28.292	0.032	0.275
Average Stem Caliber (mm)					
v. average sulfide	0.001	0.002	-0.004, 0.006	0.003	0.744
v. average salinity	-0.070	0.069	-0.210, 0.071	0.026	0.323
v. pore water temp	-0.133	0.102	-0.339, 0.074	0.046	0.201
v. substrate redox	0.001	0.003	-0.005, 0.007	0.002	0.808
v. inundation				0.215	0.009*
class 2	-0.750	0.690	-2.152, 0.651		0.284
class 3	-1.466	0.602	-2.689, -0.243		0.020*
class 4	-2.747	0.808	-4.388, -1.107		0.002*
v. % sand	-0.009	0.011	-0.032, 0.014	0.017	0.434
v. substrate pH	-0.075	0.279	-0.640, 0.490	0.002	0.790
Aboveground Biomass (g)					
v. average sulfide	0.033	0.029	-0.027, 0.093	0.037	0.272
v. average salinity	-0.772	0.869	-2.533, 0.990	0.021	0.381
v. pore water temp	-0.402	1.299	-3.040, 2.235	0.003	0.759
v. substrate redox	-0.030	0.036	-0.102, 0.042	0.019	0.408
v. inundation				0.028	0.269
class 2	13.952	9.600	-5.537, 33.441		0.155
class 3	3.485	8.380	-13.527, 20.496		0.680
class 4	-9.583	11.243	-32.407, 13.240		0.400
v. % sand	-0.099	0.144	-0.390, 0.191	0.013	0.493
v. substrate pH	0.943	3.485	-6.119, 8.005	0.002	0.788

Table 1-9. Results of multiple linear regression analysis of 2006 *Schoenoplectus pungens* plant attributes (maximum stem height, stem height growth (21 May – 24 Jun), stem density, average stem caliber, aboveground biomass) on environmental factors (average pore water sulfide (20 Apr – 5 Aug) and June sulfide (21 May – 24 Jun), substrate redox potential (5 Aug), average pore water salinity (21 May – 5 Aug), pore water temp (5 Aug), and inundation class, with additional testing of substrate texture (% sand, 1999) and pH (2005). Inundation class is treated as a categorical factor, and classes are compared to the reference (class 1), which is the zone found at the lowest tidal elevation. Models were tested as part of a Specified Analysis Plan, which reduces the risk of Type I error and allows confirmatory interpretation of results. Models tested for the purpose of additional exploratory analysis are italicized; p-values for these tests are provided but prone to Type I error. An asterisk (*) indicates $p<0.05$; a dot (.) indicates $p<0.10$. Sample sizes differ due to variation in methods and missing data: full-season models, n=34; June model, n=37.

Plant Attribute v. Environmental Factor	**Coefficient Estimate (β)**	**Standard Error**	**95% Confidence Interval**	**Adjusted R^2**	**p-value**
Maximum stem height (cm)					
v. ave sulfide + ave salinity + pore water temp + redox + inun class				0.383	0.004*
average sulfide	0.056	0.037	-0.019, 0.132		0.142
average salinity	-3.177	1.116	-5.467, -0.886		0.008*
pore water temp	-1.472	1.634	-4.824, 1.880		0.375
substrate redox	-0.093	0.042	-0.179, -0.007		0.035*
Inun class 2	-25.811	11.634	-49.682, -1.940		0.035*
Inun class 3	-16.029	9.949	-36.442, 4.384		0.119
Inun class 4	-36.510	14.950	-67.186, -5.834		0.021*
v. ave sulfide + ave salinity + pore water temp + redox + inun class + % sand + pH				0.371	0.010*
average sulfide	0.066	0.039	-0.014, 0.147		0.102
average salinity	-2.523	1.245	-5.088, 0.041		0.054.
pore water temp	-1.710	1.660	-5.129, 1.709		0.313
substrate redox	-0.097	0.042	-0.185, -0.010		0.030*
Inun class 2	-29.031	12.095	-53.942, -4.121		0.024*
Inun class 3	-24.346	12.106	-49.278, 0.587		0.055.
Inun class 4	-42.211	16.812	-76.836, -7.586		0.019*
% sand ('99)	0.083	0.181	-0.290, 0.456		0.651
substrate pH ('05)	-5.491	4.584	-14.932, 3.951		0.242
v. ave sulfide + ave salinity + pore water temp + redox + inun class + pH				0.391	0.005*
average sulfide	0.061	0.037	-0.147, 0.137		0.109
average salinity	-2.617	1.210	-5.103, -0.131		0.040*
pore water temp	-1.664	1.632	-5.018, 1.690		0.317
substrate redox	-0.096	0.042	-0.181, -0.010		0.030*
Inun class 2	-28.043	11.719	-52.132, -3.954		0.024*
Inun class 3	-23.336	11.721	-47.429, 0.758		0.057.
Inun class 4	-38.955	15.004	-69.796, -8.113		0.015*
substrate pH ('05)	-5.179	4.464	-14.355, 3.997		0.257

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	Adjusted R^2	p-value
Maximum stem height (cm) ***(cont'd)***					
v. pore water temp + inun class				0.190	0.034*
pore water temp	-3.084	1.693	-6.542, 0.375		0.079.
Inun class 2	-16.815	11.085	-39.453, 5.823		0.140
Inun class 3	-19.633	9.938	-39.930, 0.663		0.058.
Inun class 4	-33.673	16.435	-67.238, -0.107		0.049*
v. pore water temp + inun class + % sand + pH				0.192	0.058.
pore water temp	-2.849	1.700	-6.330, 0.633		0.105
Inun class 2	-16.261	11.081	-38.960, 6.438		0.153
Inun class 3	-26.059	10.893	-48.373, -3.746		0.024*
Inun class 4	-35.487	17.700	-71.743, 0.770		0.055.
% sand ('99)	0.018	0.192	-0.377, 0.412		0.928
substrate pH ('05)	-6.553	4.566	-15.906, 2.800		0.162
v. pore water temp + inun class + pH				0.220	0.030*
pore water temp	-2.852	1.670	-6.267, 0.564		0.099.
Inun class 2	-16.284	10.888	-38.551, 5.984		0.146
Inun class 3	-26.002	10.688	-47.861, -4.143		0.021*
Inun class 4	-34.888	16.156	-67.930, -1.846		0.039*
pH ('05)	-6.549	4.487	-15.725, 2.628		0.155
June stem height growth (cm)					
v. June sulfide + June salinity + inun class				0.330	0.003*
June sulfide	0.001	0.010	-0.020, 0.022		0.903
June salinity	-1.183	0.565	-2.334, -0.032		0.044*
Inun class 2	-6.929	5.792	-18.727, 4.868		0.240
Inun class 3	-4.107	4.562	-13.400, 5.186		0.375
Inun class 4	-23.559	5.857	-35.488, -11.629		<0.001*
v. June sulfide + June salinity + inun class + Aug temp + Aug redox				0.276	0.020*
June sulfide	-0.004	0.010	-0.023, 0.016		0.717
June salinity	-1.385	0.570	-2.552, -0.218		0.022*
Inun class 2	-10.708	5.660	-22.302, 0.886		0.069.
Inun class 3	-8.495	4.617	-17.952, 0.962		0.076.
Inun class 4	-19.429	7.145	-34.065, -4.794		0.011*
pore water temp	-0.894	0.752	-2.434, 0.647		0.245
substrate redox	-0.048	0.021	-0.091, -0.004		0.032*

v. June sulfide + June salinity + inun class + Aug temp + Aug redox + % sand				0.249	0.039*
June sulfide	-0.004	0.010	-0.025, 0.018		0.727
June salinity	-1.390	0.594	-2.609, -0.171		0.027*
Inun class 2	-10.679	5.811	-22.603, 1.244		0.077.
Inun class 3	-8.478	4.722	-18.168, 1.212		0.084.
Inun class 4	-19.320	7.818	-35.362, -3.279		0.020*
pore water temp	-0.892	0.767	-2.465, 0.680		0.255
substrate redox	-0.048	0.022	-0.092, -0.003		0.036*
% sand ('99)	-0.003	0.087	-0.182, 0.176		0.970
v. June sulfide + June salinity + inun class + Aug temp + Aug redox + pH				0.322	0.013*
June sulfide	<0.001	0.001	-0.020, 0.020		1.000
June salinity	-1.236	0.558	-2.381, -0.091		0.035*
Inun class 2	-11.180	5.482	-22.425, 0.073		0.051.
Inun class 3	-11.700	4.844	-21.639, -1.759		0.023*
Inun class 4	-19.430	6.912	-33.610, -5.246		0.009*
pore water temp	-0.928	0.728	-2.422, 0.565		0.213
substrate redox	-0.050	0.021	-0.092, -0.008		0.022*
substrate pH ('05)	-3.178	1.860	-6.994, 0.639		0.099.
v. Aug temp + inun class				0.143	0.066.
pore water temp	-1.129	0.780	-2.721, 0.462		0.158
Inun class 2	-8.180	4.993	-18.363, 2.002		0.111
Inun class 3	-7.844	4.544	-17.112, 1.424		0.094.
Inun class 4	-15.196	7.454	-30.399, 0.007		0.050.
v. Aug temp + inun class + % sand + pH				0.162	0.080.
pore water temp	-1.087	0.773	-2.667, 0.493		0.170
Inun class 2	-7.149	4.991	-17.357, 3.059		0.163
Inun class 3	-10.592	4.800	-20.409, -0.776		0.035*
Inun class 4	-15.355	7.825	-31.358, 0.648		0.059.
% sand ('99)	0.016	0.085	-0.159, 0.190		0.857
substrate pH ('05)	-3.231	1.989	-7.298, 0.836		0.115
v. Aug temp + inun class + % sand				0.116	0.121
pore water temp	-1.124	0.793	-2.744, 0.496		0.167
Inun class 2	-8.086	5.092	-18.484, 2.313		0.123
Inun class 3	-7.858	4.616	-17.286, 1.570		0.099.
Inun class 4	-15.754	8.032	-32.157, 0.649		0.059.
% sand ('99)	0.018	0.088	-0.161, 0.198		0.836
v. Aug temp + inun class + pH				0.189	0.044*
pore water temp	-1.091	0.760	-2.643, 0.460		0.161
Inun class 2	-7.227	4.892	-17.218, 2.764		0.150
Inun class 3	-10.586	4.722	-20.229, -0.944		0.033*
Inun class 4	-14.881	7.256	-29.699, -0.062		0.049*
substrate pH ('05)	-3.239	1.956	-7.233, 0.756		0.108

Plant Attribute v. Environmental Factor	**Coefficient Estimate (β)**	**Standard Error**	**95% Confidence Interval**	**Adjusted R^2**	**p-value**
Stem density (stems/0.0625 m^2)					
v. ave sulfide + ave salinity + pore water temp + redox + inun class				0.111	0.177
average sulfide	-0.070	0.093	-0.262, 0.121		0.457
average salinity	-1.138	2.818	-6.921, 4.645		0.690
pore water temp	4.683	4.124	-3.779, 13.146		0.266
substrate redox	0.099	0.106	-0.118, 0.316		0.356
Inun class 2	55.628	29.372	-4.638, 115.894		0.069.
Inun class 3	21.959	25.117	-29.577, 73.496		0.390
Inun class 4	90.462	37.745	13.017, 167.908		0.024*
v. ave sulfide + ave salinity + pore water temp + redox + inun class + % sand + pH				0.195	0.097.
average sulfide	-0.030	0.093	-0.221, 0.161		0.749
average salinity	-1.194	2.964	-7.299, 4.911		0.690
pore water temp	4.557	3.952	-3.581, 12.696		0.260
substrate redox	0.089	0.101	-0.119, 0.297		0.387
Inun class 2	49.433	28.792	-9.865, 108.731		0.098.
Inun class 3	24.905	28.818	-34.446, 84.256		0.396
Inun class 4	60.990	40.020	-21.433,143.413		0.140
% sand ('99)	0.866	0.431	-0.021, 1.753		0.055.
substrate pH ('05)	6.308	10.913	-16.168, 28.783		0.568
v. pore water temp + inun class				0.133	0.081.
pore water temp	3.486	3.684	-4.036, 11.009		0.352
Inun class 2	31.887	24.111	-17.355, 81.128		0.196
Inun class 3	9.386	21.617	-34.763, 53.534		0.667
Inun class 4	77.937	35.750	4.925, 150.949		0.037*
v. pore water temp + inun class + % sand + pH				0.245	0.027*
pore water temp	3.567	3.454	-3.507, 10.642		0.311
Inun class 2	32.959	22.517	-13.165, 79.084		0.154
Inun class 3	8.561	22.135	-36.780, 53.902		0.702
Inun class 4	44.717	35.966	-28.955,118.390		0.224
% sand ('99)	0.988	0.391	0.187, 1.789		0.018*
substrate pH ('05)	2.202	9.278	-16.803, 21.207		0.814

Plant Attribute v. Environmental Factor	Coefficient Estimate (β)	Standard Error	95% Confidence Interval	Adjusted R^2	p-value
Average stem caliber (mm)					
v. ave sulfide + ave salinity + pore water temp + redox + inun class				0.093	0.210
average sulfide	0.001	0.003	-0.005, 0.006		0.811
average salinity	-0.045	0.083	-0.216, 0.125		0.591
pore water temp	-0.191	0.121	-0.441, 0.058		0.127
substrate redox	-0.002	0.003	-0.009, 0.004		0.490
Inun class 2	-0.741	0.865	-2.517, 1.034		0.399
Inun class 3	-1.563	0.740	-3.081, -0.045		0.044*
Inun class 4	-1.385	1.112	-3.667, 0.896		0.224
v. ave sulfide + ave salinity + pore water temp + redox + inun class + % sand + pH				0.044	0.352
average sulfide	0.001	0.003	-0.005, 0.007		0.650
average salinity	-0.022	0.094	0.216, 0.172		0.814
pore water temp	-0.201	0.126	-0.459, 0.058		0.122
substrate redox	-0.002	0.003	-0.009, 0.004		0.459
Inun class 2	-0.906	0.915	-2.790, 0.978		0.332
Inun class 3	-1.835	0.916	-3.722, 0.051		0.056.
Inun class 4	-1.827	1.272	-4.446, 0.793		0.163
% sand ('99)	0.010	0.014	-0.018, 0.038		0.473
substrate pH ('05)	-0.144	0.347	-0.859, 0.570		0.681
v. pore water temp + inun class				0.162	0.053.
pore water temp	-0.211	0.106	-0.427, 0.005		0.055.
Inun class 2	-0.543	0.692	-1.956, 0.869		0.438
Inun class 3	-1.540	0.620	-2.806, -0.274		0.019*
Inun class 4	-1.262	1.025	-3.356, 0.832		0.228
v. pore water temp + inun class + % sand + pH				0.119	0.143
pore water temp	-0.206	0.109	-0.429, 0.017		0.069.
Inun class 2	-0.525	0.710	-1.979, 0.929		0.466
Inun class 3	-1.671	0.698	-3.100, -0.241		0.024*
Inun class 4	-1.540	1.134	-3.862, 0.783		0.185
% sand ('99)	0.008	0.012	-0.018, 0.033		0.545
substrate pH ('05)	-0.111	0.292	-0.710, 0.488		0.708

Plant Attribute v. Environmental Factor	**Coefficient Estimate (β)**	**Standard Error**	**95% Confidence Interval**	**Adjusted R^2**	**p-value**
Aboveground biomass (g)					
v. ave sulfide + ave salinity + pore water temp + redox + inun class				-0.091	0.754
average sulfide	0.031	0.037	-0.046, 0.107		0.420
average salinity	-1.761	1.132	-4.083, 0.560		0.131
pore water temp	0.971	1.656	-2.426, 4.369		0.562
substrate redox	-0.005	0.042	-0.091, 0.082		0.913
Inun class 2	10.060	11.792	-14.136, 34.256		0.401
Inun class 3	5.560	10.084	-15.131, 26.251		0.586
Inun class 4	4.762	15.154	-26.331, 35.855		0.756
v. ave sulfide + ave salinity + pore water temp + redox + inun class + % sand + pH				-0.157	0.869
average sulfide	0.037	0.040	-0.046, 0.120		0.367
average salinity	-1.695	1.288	-4.348, 0.959		0.200
pore water temp	0.927	1.717	-2.609, 4.464		0.594
substrate redox	-0.007	0.044	-0.097, 0.084		0.883
Inun class 2	8.877	12.512	-16.892, 34.646		0.485
Inun class 3	5.004	12.523	-20.789, 30.796		0.693
Inun class 4	0.229	17.392	-35.590, 36.047		0.990
% sand ('99)	0.124	0.187	-0.262, 0.509		0.515
substrate pH ('05)	0.208	4.742	-9.559, 9.975		0.965
v. pore water temp + inun class				-0.080	0.832
pore water temp	-0.113	1.491	-3.159, 2.933		0.940
Inun class 2	10.121	9.762	-9.816, 30.058		0.308
Inun class 3	-0.497	8.752	-18.372, 17.378		0.955
Inun class 4	1.777	14.475	-27.784, 31.338		0.903
v. pore water temp + inun class + % sand + pH				-0.133	0.912
pore water temp	-0.036	1.534	-3.178, 3.106		0.981
Inun class 2	10.404	10.002	-10.084, 30.891		0.307
Inun class 3	-2.429	9.832	-22.568, 17.711		0.807
Inun class 4	-2.611	15.975	-35.335, 30.112		0.871
% sand ('99)	0.120	0.174	-0.236, 0.476		0.495
substrate pH ('05)	-1.616	4.121	-10.057, 6.826		0.698

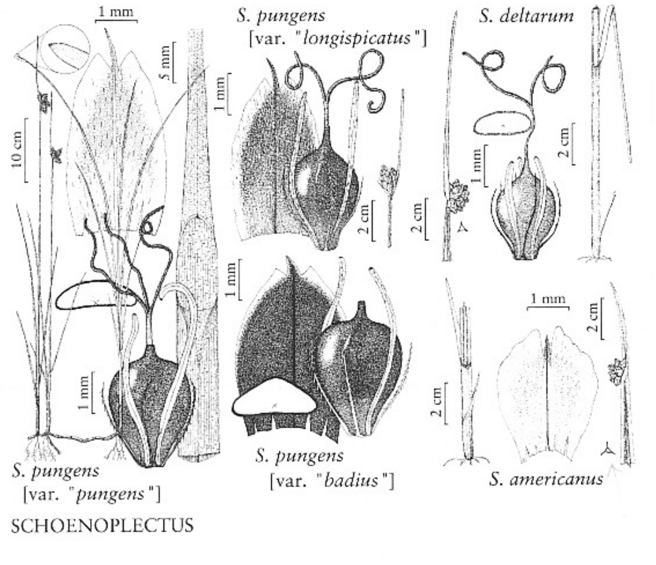


Figure 1-1. Top drawings of *Schoenoplectus pungens* (formerly called *Scirpus americanus* in the Pacific Northwest) by Jeanne R. Janish are from *Vascular Plants of the Pacific Northwest* (Hitchcock et al. 1969:372). Bottom drawings by Susan A. Reznicek are from the *Schoenoplectus* section in *Flora of North America: North of Mexico* (Smith (2002:51). *S. pungens var. badius* is native to the coastal marshes of the Pacific Northwest.

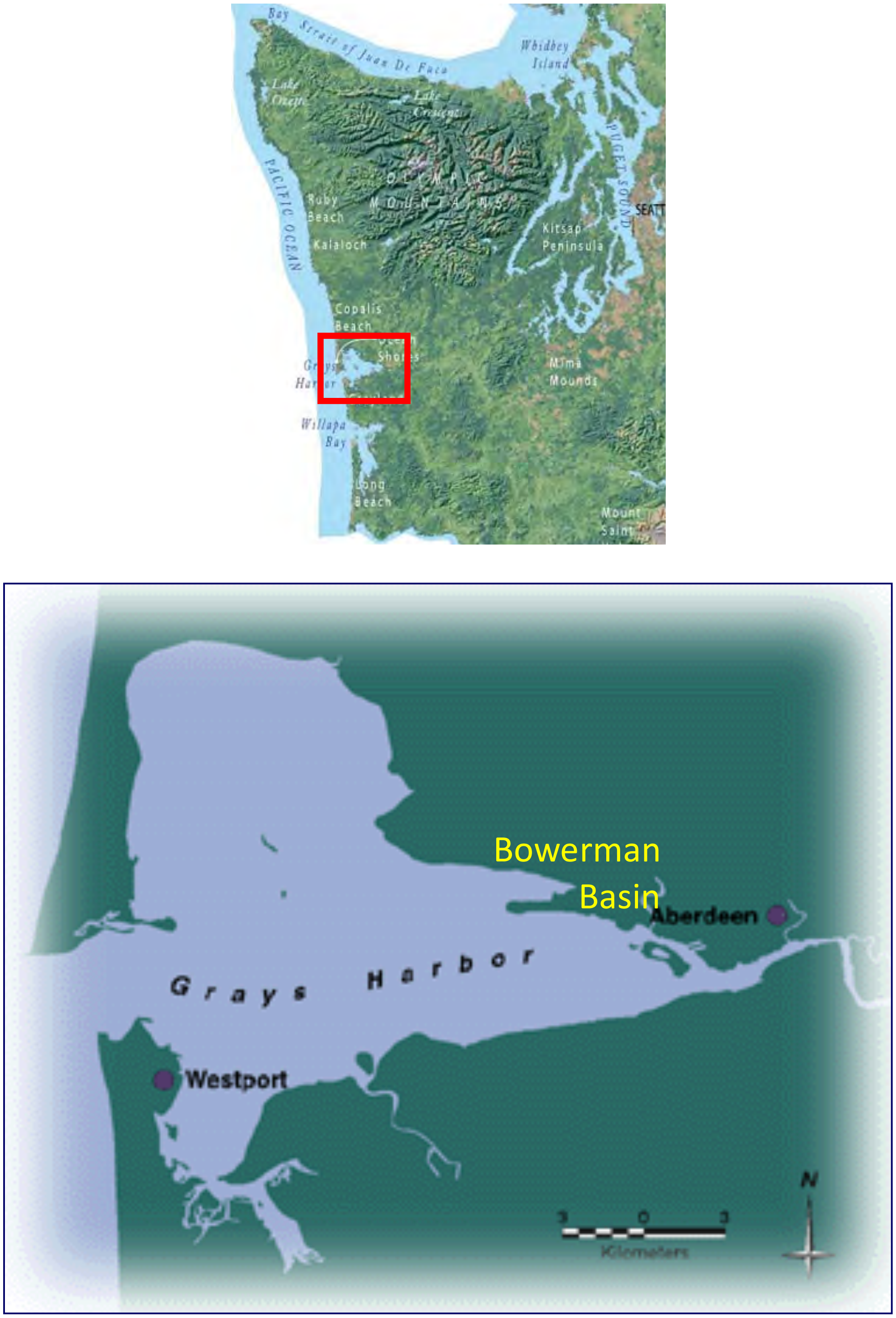
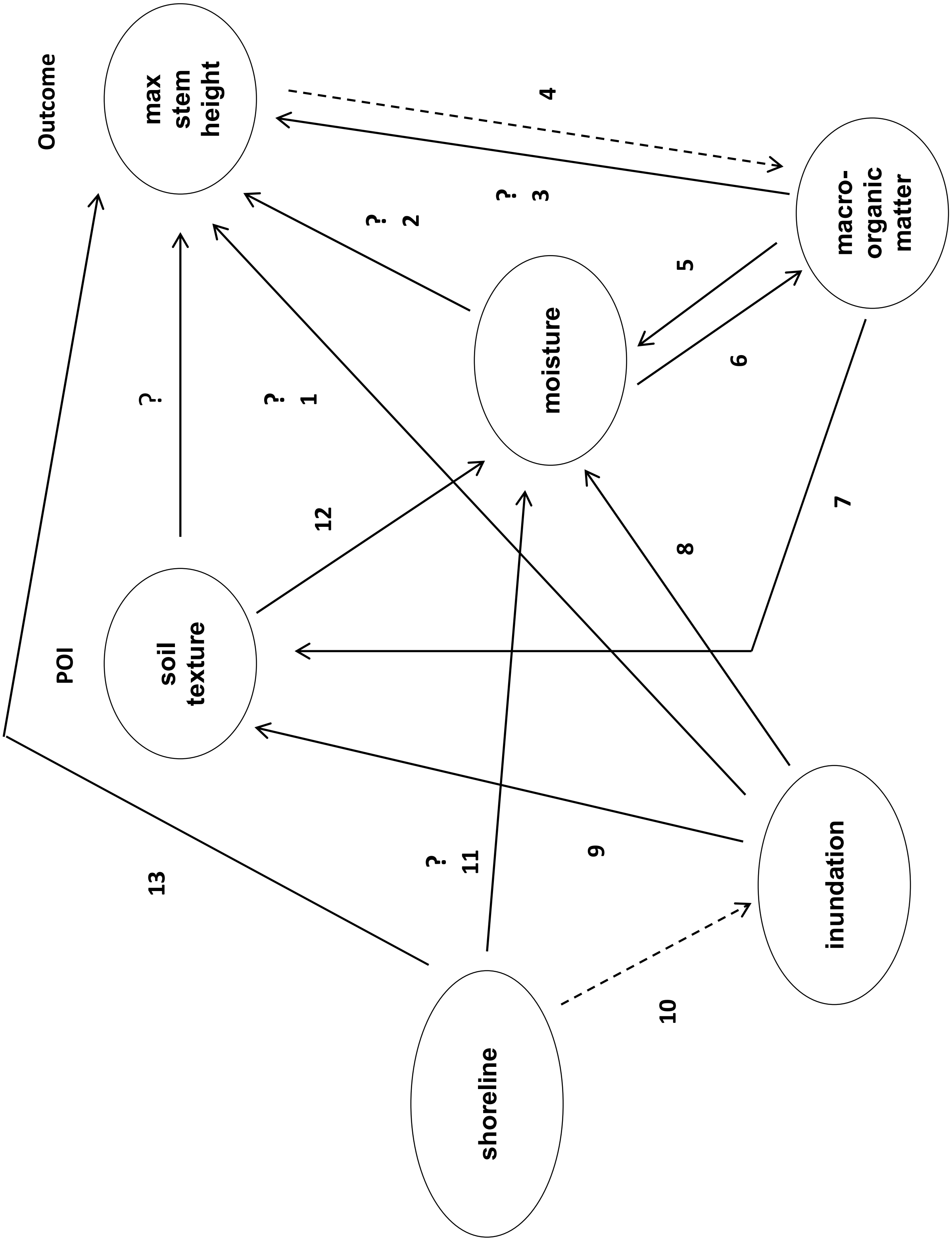


Figure 1-2. Regional maps. Top: Western Washington with Grays Harbor highlighted (source: www.bentler.us). Bottom: Bowerman Basin, the site of Grays Harbor Wildlife Refuge (source: Pacific Northwest Coastal Ecosystem Regional Study).

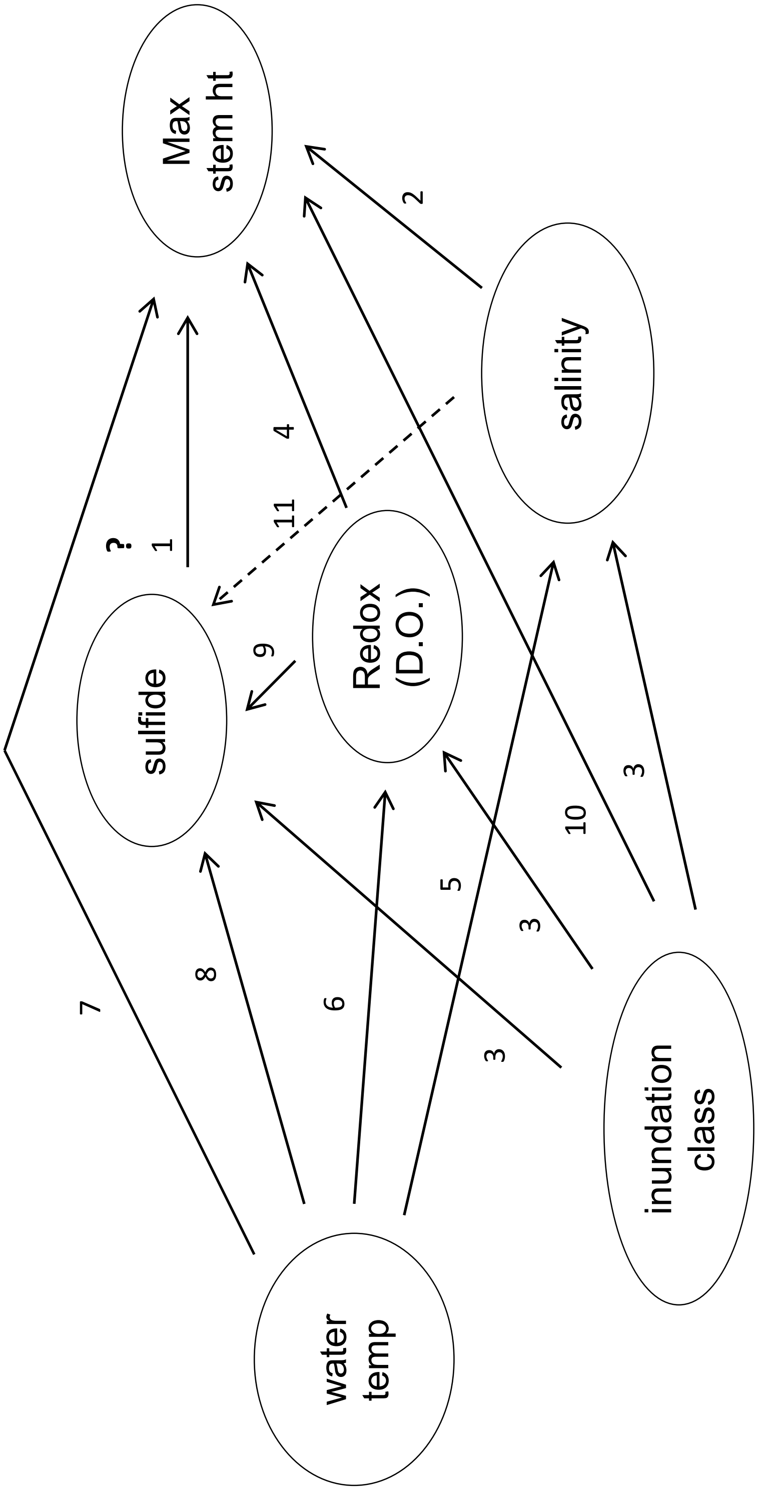
Figure 1-3. Native American and First Nations baskets made with sweetgrass. Top row: Loa Ryan (Ts'msyen). (Photos: Mitchell Almaguer-Bay) Middle row: Quinault. Bottom row: Louisa Pulsifer (Skokomish). (Photos in bottom two rows: Burke Museum of Natural History and Culture; object numbers 2.5E1149 and 2.5E1618, respectively)

Figure 1-4. Locations of transects in Grays Harbor National Wildlife Refuge, Washington. Transects were established in *Schoenoplectus pungens* stands and placed perpendicular to the shoreline and parallel to the elevation gradient. A sampling point (quadrat) was located 1 meter in from the edge of the stand, and two or three additional sampling points were located at evenly spaced intervals (≤11 meters) in between the end points. Photos: Washington State Department of Ecology, Shoreline Photo Viewer, 2006-7 (https://fortress.wa.gov/ecy/shorephotoviewer/).


Outcome
max stem height
POI
soil texture
moisture
macro-organic matter
inundation
shoreline
?
? 1
? 2
? 3
4
5
6
7
8
9
10
? 11
12
13

1. Flooding decreases O_2 levels (but can also replenish them), which affects root and shoot growth, unless plant is adapted to low O_2 conditions
2. Moisture provides water for photosynthesis and osmoregulation but can also prevent O_2 from reaching roots where it is used in respiration.
3. Organic matter is a source of nutrients but can also bind up nutrients.
4. More plant growth → more organic matter in substrate, especially from roots but also from production of aboveground biomass.
5. Macro-organic matter (MOM) retains moisture.
6. Moisture slows decomposition, so MOM accumulates.
7. Organic matter decomposes to fine particles, including silt.
8. Inundation with daily tides delivers moisture to marsh.
9. Quadrats at lower elevations have finer-grained substrate, which is deposited on receding tides. Incoming tides deposit coarser sediments at higher elevations.
10. Shoreline topography affects elevation and therefore flooding by tides.
11. Shoreline location may determine whether or not freshwater flows into marsh from overland flow or groundwater.
12. Fine-grained substrate drains slowly. Coarse substrate drains quickly unless water table is high.
13. Latent variables: a) orientation of shoreline affects exposure ("energy") and therefore soil texture; b) topography and geology affect freshwater input, which affects moisture and salinity; c) site history may include deposition of sandy dredged material.

Figure 1-5. Example of directed acyclic graph used to construct models with physical variables for testing with multiple regression in the Specified Analysis Plan. Here, the parameter of interest (POI) was soil texture, and the outcome, or plant attribute of interest, was maximum stem height. Other physical environmental variables measured in 1999 are potentially confounding variables. Latent variables are not measured but may be important in interpreting results. Relationships that are uncertain are marked with a question mark (?). Dashed lines represent indirect effects.


Max stem ht
salinity
sulfide
Redox (D.O.)
water temp
inundation class
?
1
2
3
3
3
3
4
5
6
7
8
9
10
11

1. At high levels, sulfide inhibits plant growth. At low levels, it may be a nutrient.
2. Salinity is a stress on plant growth. Although saline levels confer a competitive advantage on species that can tolerate/are adapted to saline conditions, higher salinities are correlated with slower plant growth for a given species.
3. Tidal inundation (sea water) is the source of a) salinity, b) sulfate, which is chemically reduced to sulfide in saturated conditions, and c) saturation that leads to low redox (and low dissolved oxygen levels) as well as tidal flushing that brings with it aerated (oxygenated) water that can keep redox (and oxygen) levels relatively high.
4. Low levels of dissolved oxygen (needed by plant roots) would be correlated with slow growth *unless* the plant has produced aerenchyma, which transport oxygen from above-ground parts to below-ground roots.
5. Higher pore water temperature is correlated with higher evaporation, which could lead to higher concentrations of salt.
6. Higher pore water temperature could lead to evaporation of gaseous oxygen and increased biological oxygen demand and result in low levels of dissolved oxygen, which would lead to low redox.
7. Higher water temperature may be correlated with higher metabolic rates and faster growth.
8. H_2S gas can evaporate at higher temperatures, so sulfide concentrations could decrease.
9. Low redox should be associated with higher sulfide concentration because sulfur is chemically reduced at low redox levels.
10. Inundation (flooding) by tides decreases light that reaches photosynthetic tissue which would decrease growth.
11. Salinity and sulfide may be associated or correlated because seawater is a common source of both salts (in salinity) and sulfate (which is reduced to sulfide).

Figure 1-6. Example of directed acyclic graph used to construct models with chemical variables for testing with multiple regression in the Specified Analysis Plan. Here, the parameter of intrest (POI) was sulfide, and the outcome, or plant attribute of interest, was maximum stem height. Other variables measured in 2006 are potentially confounding variables. Dashed line indicates indirect effect.

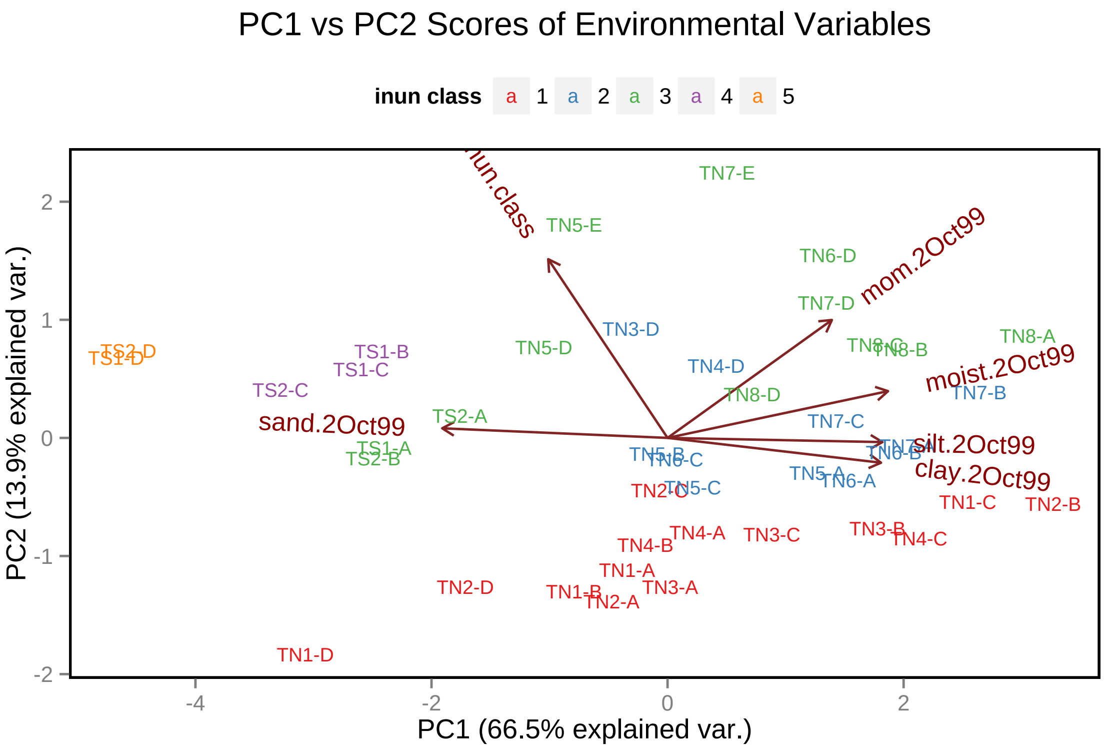


Figure 1-7. PCA biplot of 1999 environmental variables with quadrats coded by inundation class. Variables included soil texture (% sand, % silt, % clay), % moisture, % macro-organic matter (MOM), and inundation class. Inundation class 1 was at lowest and 5 was at highest elevation. Inundation classes 4 and 5 were combined in multiple regression analysis because of small number of quadrats. Quadrat labels refer to north (N) or south (S) shore of the Grays Harbor National Wildlife Refuge, transect number (1-8), and quadrat (A-E). One quadrat (TN4-E) with an outlier % MOM value was omitted to permit interpretation of general patterns among variables. N=42. See Table 1-2 for rotation matrix and importance of components.

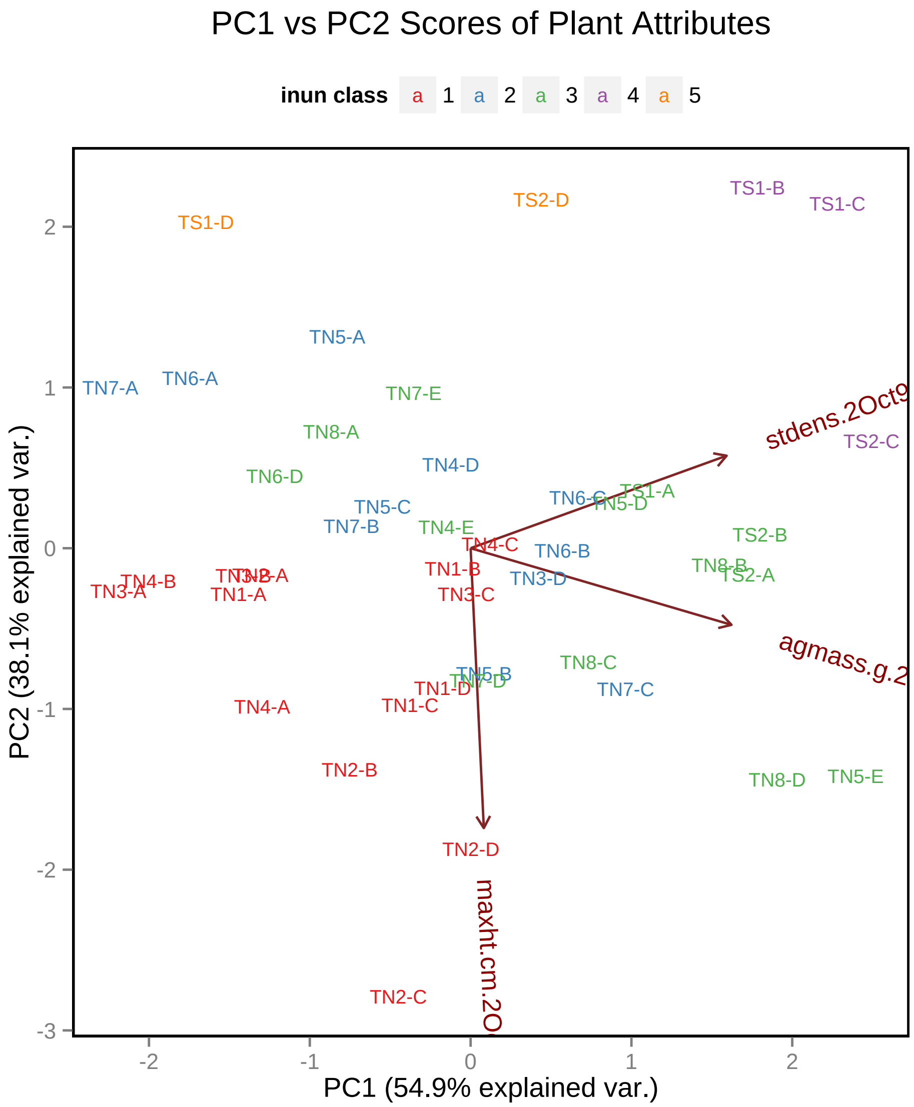


Figure 1-8. PCA biplot of 1999 *S. pungens* attributes (maximum stem height, stem density, and aboveground biomass) with quadrats coded by inundation class. Inundation class 1 was at lowest elevation and 5 was at highest. Inundation classes 4 and 5 were combined in multiple regression analysis because of small number of quadrats. Quadrat labels refer to north (N) or south (S) shore of the Grays Harbor National Wildlife Refuge, transect number (1-8), and quadrat (A-E). N=43. See Table 1-3 for rotation matrix and importance of components.

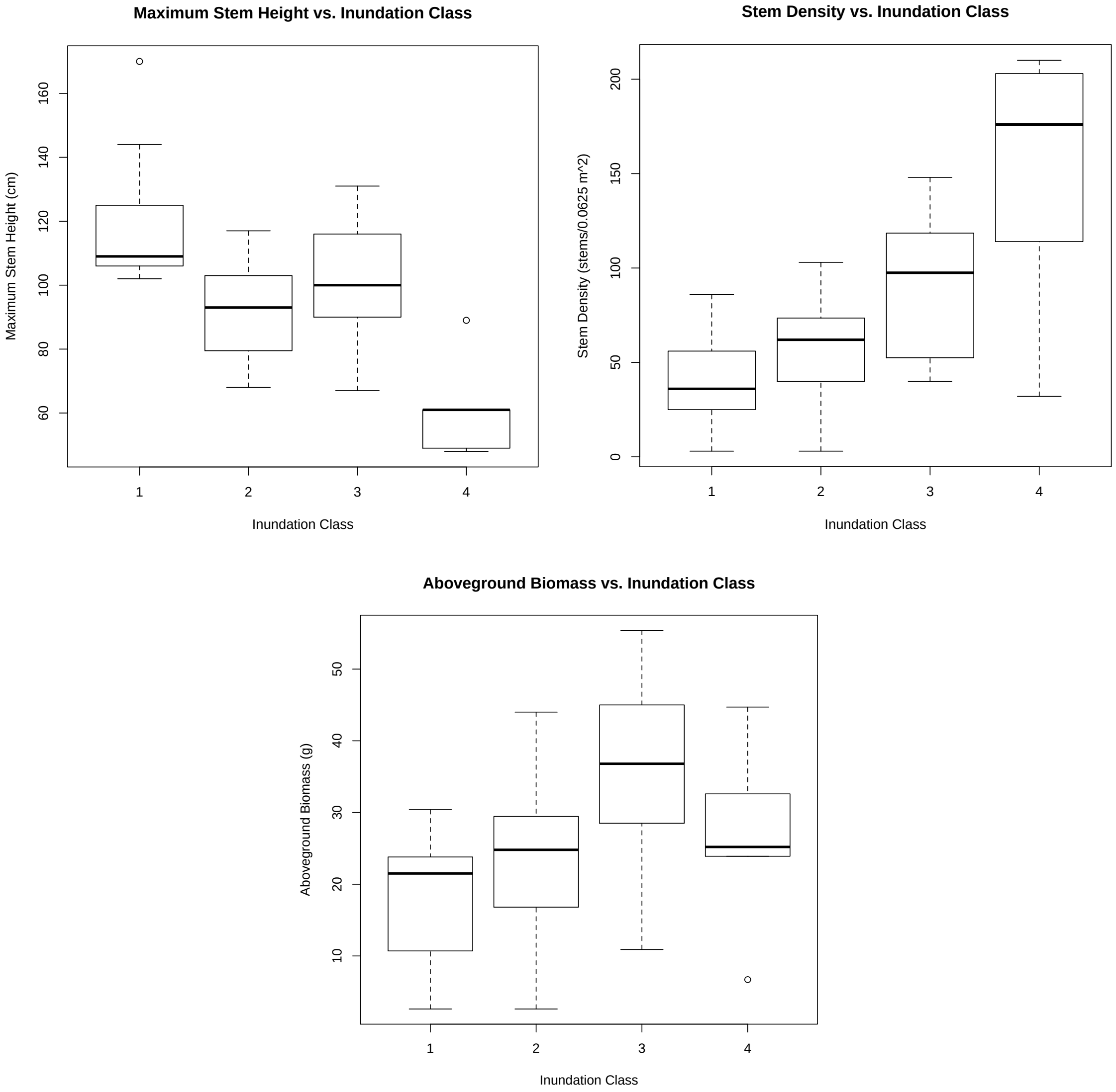


Figure 1-9. Boxplots of maximum stem height (cm), stem density (stems/0.0625 m2), and aboveground biomass (g) in 1999 vs. inundation class, which is a categorical variable and corresponds to zones across an elevation gradient in the intertidal marsh. N=43. See Table 1-4 for ANOVA results, which were conducted for descriptive purposes.

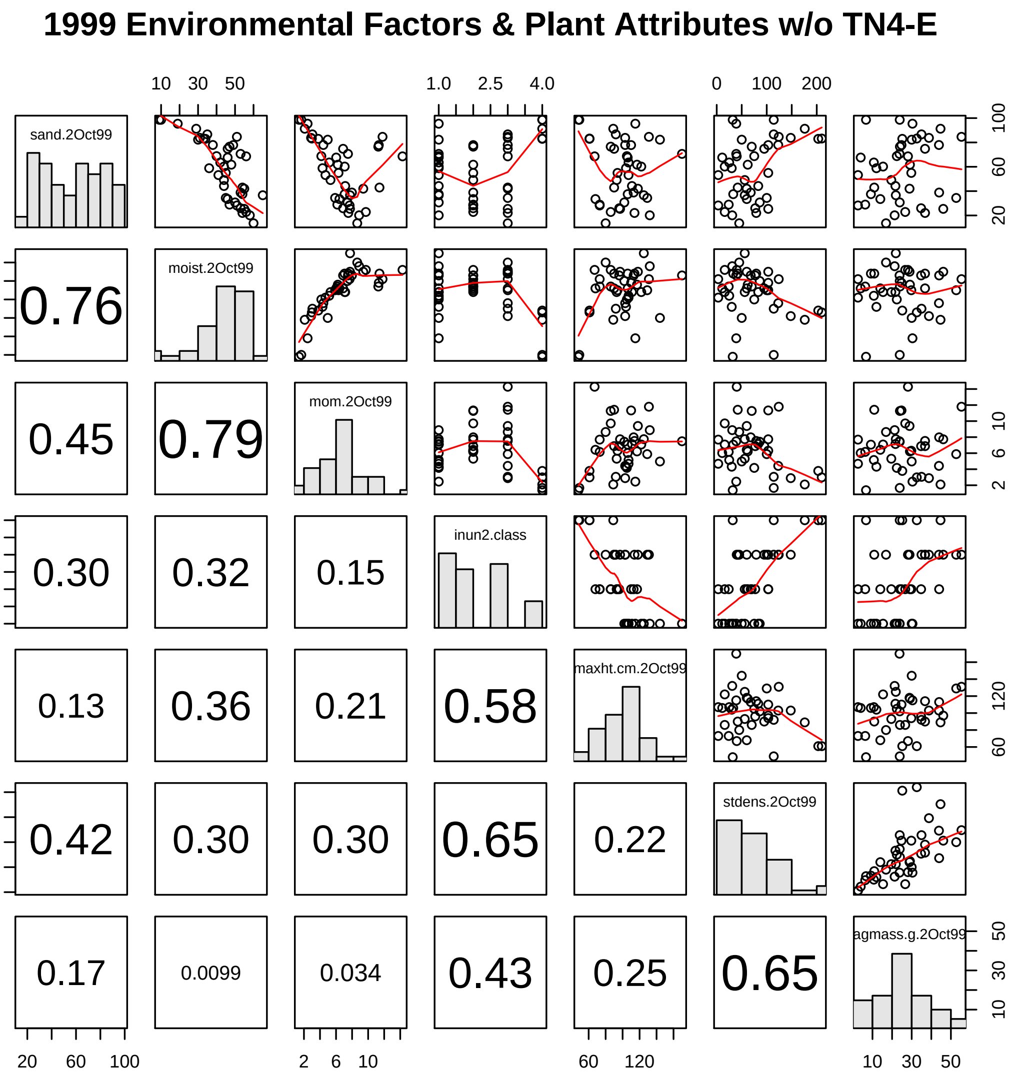


Figure 1-10. Paired plots for 1999 *S. pungens* attributes and environmental variables, with lowess smoother lines in each scatterplot, histograms of each variable, and Pearson correlation coefficients (+ or - direction determined visually) for all paired variables. Environmental variables include % sand, % moisture, % macro-organic matter (MOM), and inundation class. Soil texture was represented by % sand, since all particle sizes were highly correlated or autocorrelated. One quadrat (TN4-E) was omitted from this analysis due to an outlier % MOM value that may have resulted from a methodology error in the field or lab. Inundation class is a categorical variable based on zones of tidal elevation: Class 1 is at lowest and 4 is at highest elevation. The strong correlation between inundation class and maximum stem height was consistent with field observations, but cannot be interpreted strictly since inundation class is a categorical variable. N=42.

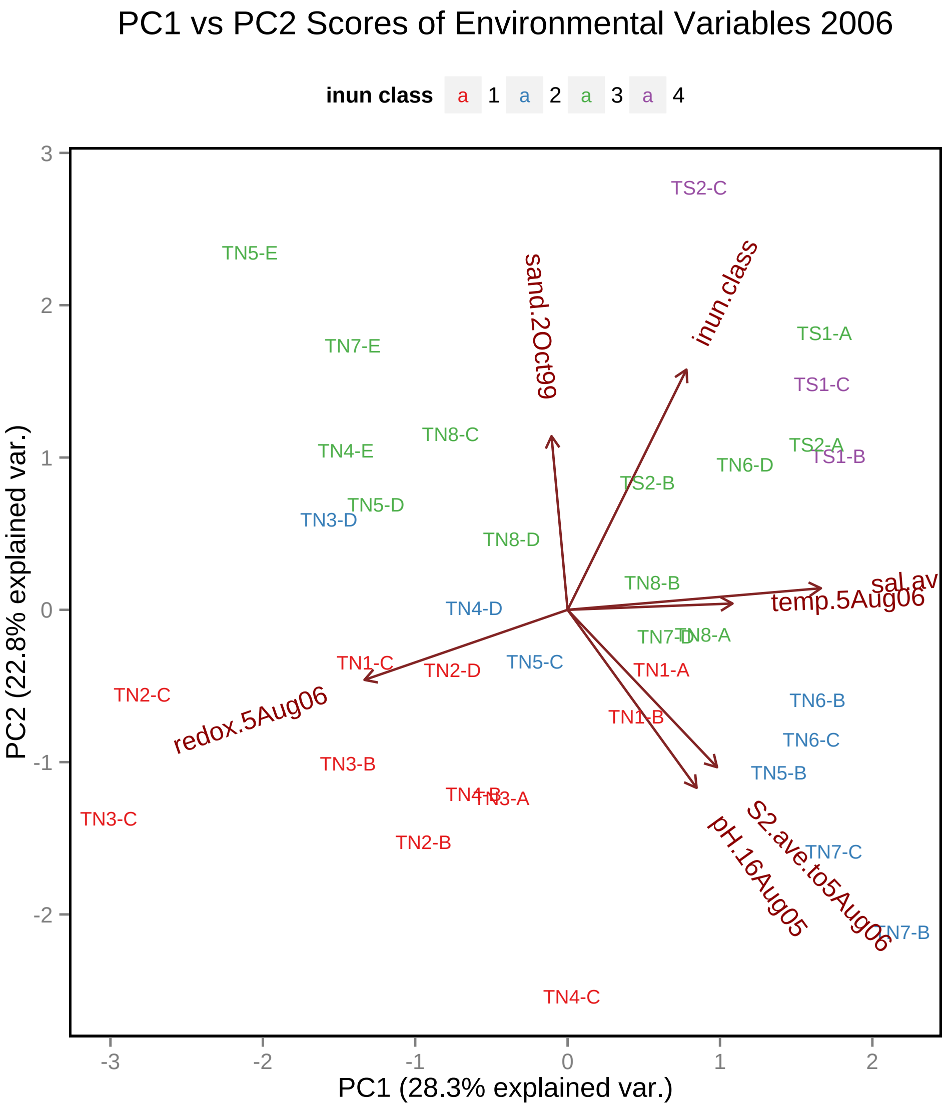


Figure 1-11. PCA biplot of environmental factors (sulfide concentrations, salinity, pore water temperature, redox potential, inundation class) measured in 2006. Sulfide concentrations in pore water were averaged over the period 20 April to 5 August. Pore water salinity was averaged over the period 21 May to 5 August. Percent sand from 1999 was added because sand was shown to be a statistically significant factor in 1999 and because the substrate texture was expected to be relatively stable over the duration of this study. pH measured in soil cores from 2005 was also included because it was expected to be relatively stable from year to year. Four quadrats were omitted from this analysis because of missing data in sulfide concentrations and/or pore water temperature: TN1-D and TN2-A vials could not be found in May, and TS1-D and TS2-D vials drained over several weeks and were empty in August. N=35. See Table 1-6 for rotation matrix and importance of components. Similar PCA results were obtained for the period of fastest stem growth (21 May-21 June).

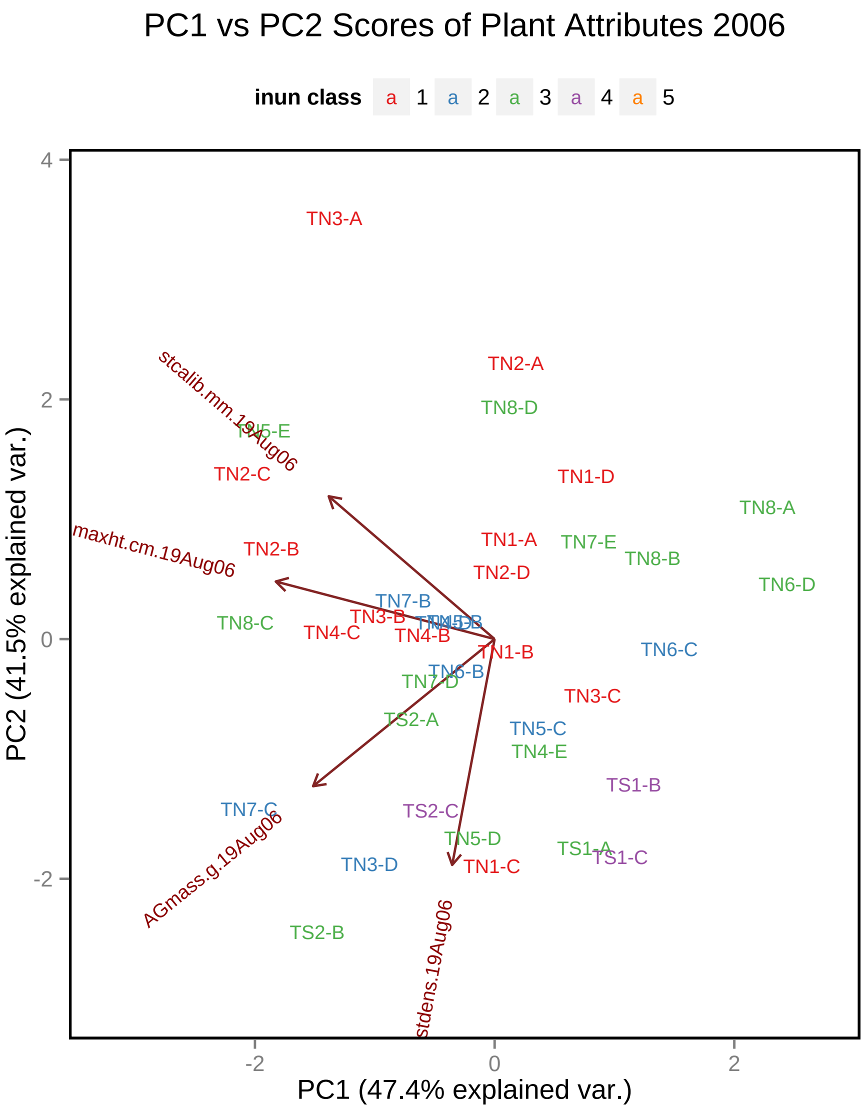


Figure 1-12. PCA biplot of 2006 *S. pungens* attributes (maximum stem height, stem density, stem caliber, and aboveground biomass) with quadrats coded by inundation class. Inundation class 1 was at lowest and 5 was at highest elevation. Inundation classes 4 and 5 were combined in multiple regression analysis because of small number of quadrats. Quadrat labels refer to north (N) or south (S) shore of the Grays Harbor National Wildlife Refuge, transect number (1-8), and quadrat (A-E). N=39. See Table 1-7 for rotation matrix and importance of components.

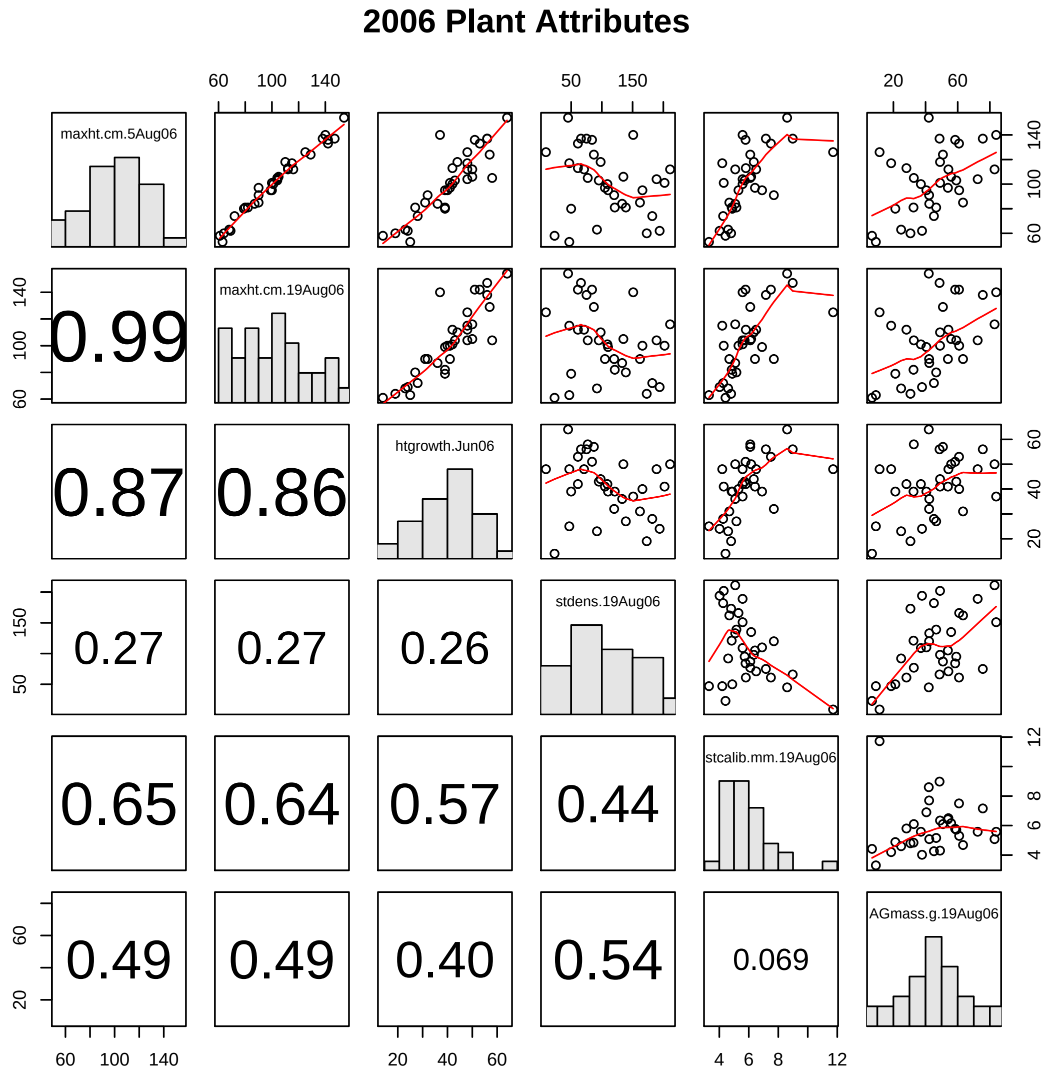


Figure 1-13. Paired plots, with lowess smoother lines, of 2006 *S. pungens* attributes, histograms of each attribute, and Pearson correlation coefficients (+ or - direction determined visually) for all paired variables. From left to right, attributes are maximum stem height (5 August), maximum stem height (19 August), June stem height growth (21 May – 24 June), stem density (19 August), average stem caliber (19 August), and aboveground biomass (19 August). N=38.

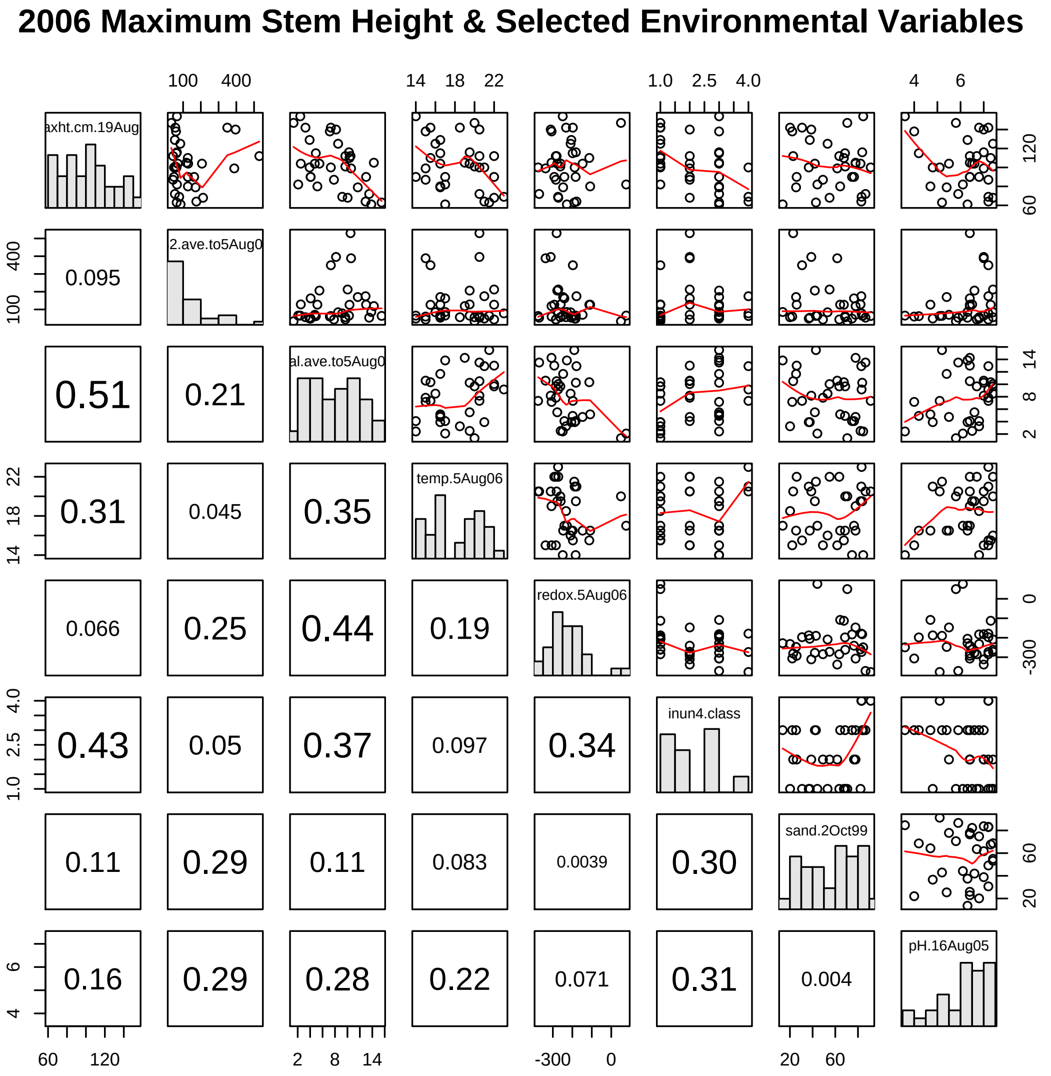


Figure 1-14. Paired plots, with lowess smoother lines, of maximum stem height (19 August 2006) and selected environmental variables used in specified models, as well as histograms of these variables and Pearson correlation coefficients (+ or - direction determined visually) for all paired variables. From left to right: maximum stem height (19 Aug 2006), average pore water sulfide concentration (20 April – 5 August 2006), average pore water salinity (21 May – 5 August 2006), pore water temperature (5 August 2006), substrate redox potential (5 August 2006), inundation class (a categorical variable based on tidal elevation zones), % sand (2 Oct 1999), and substrate pH (16 August 2005). Four quadrats were omitted from this analysis because of missing data in sulfide concentrations and/or pore water temperature: TN1-D and TN2-A vials could not be found in May, and TS1-D and TS2-D vials drained over several weeks and were empty in August. N=35.

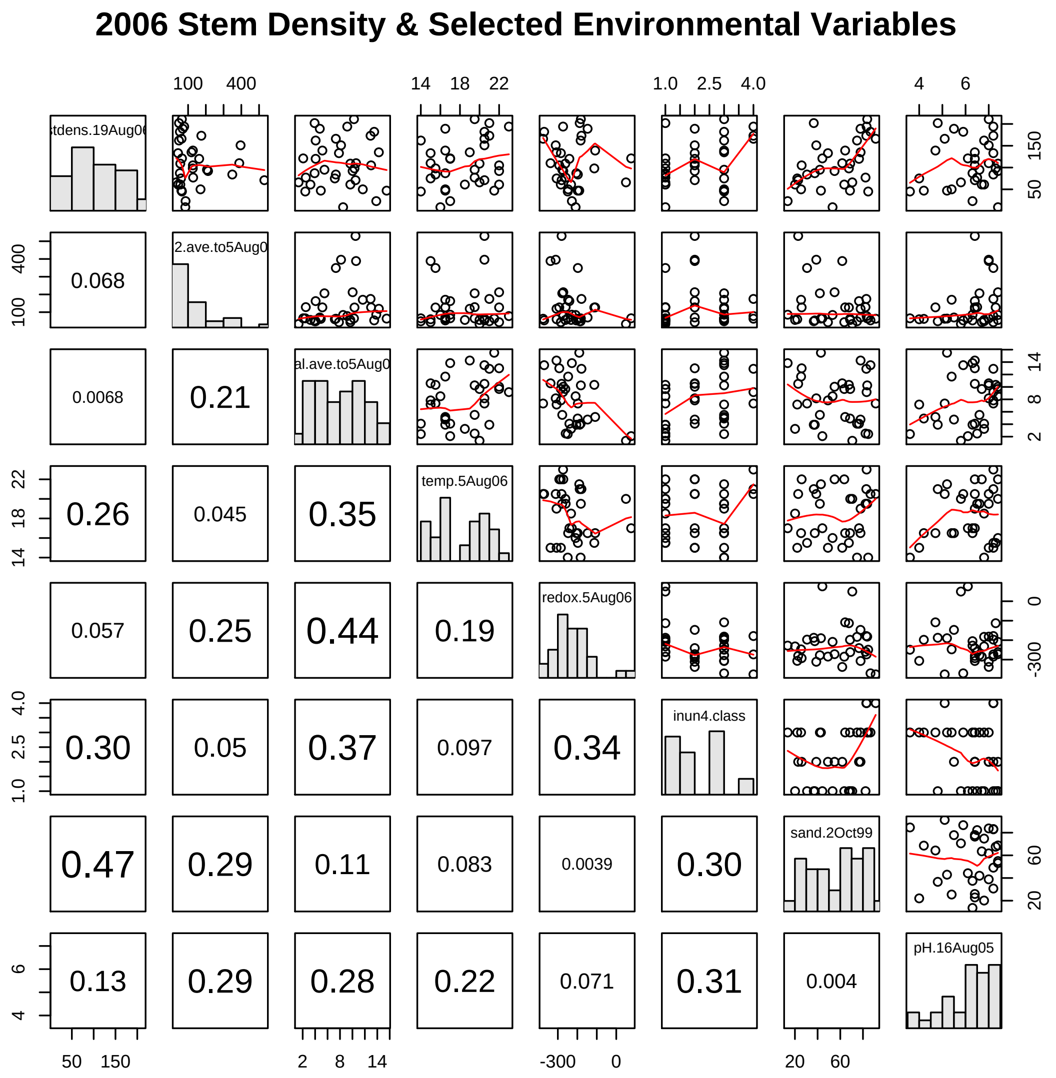


Figure 1-15. Paired plots, with lowess smoother lines, of stem density (19 August 2006) and selected environmental variables used in specified models, as well as histograms of these variables and Pearson correlation coefficients (+ or – direction determined visually) for all paired variables. From left to right: stem density (19 Aug 2006), average pore water sulfide concentration (20 April – 5 August 2006), average pore water salinity (21 May – 5 August 2006), pore water temperature (5 August 2006), substrate redox potential (5 August 2006), inundation class (a categorical variable based on tidal elevation zones), % sand (2 Oct 1999), and substrate pH (16 August 2005). Four quadrats were omitted from this analysis because of missing data in sulfide concentrations and/or pore water temperature: TN1-D and TN2-A vials could not be found in May, and TS1-D and TS2-D vials drained over several weeks and were empty in August. N=35.

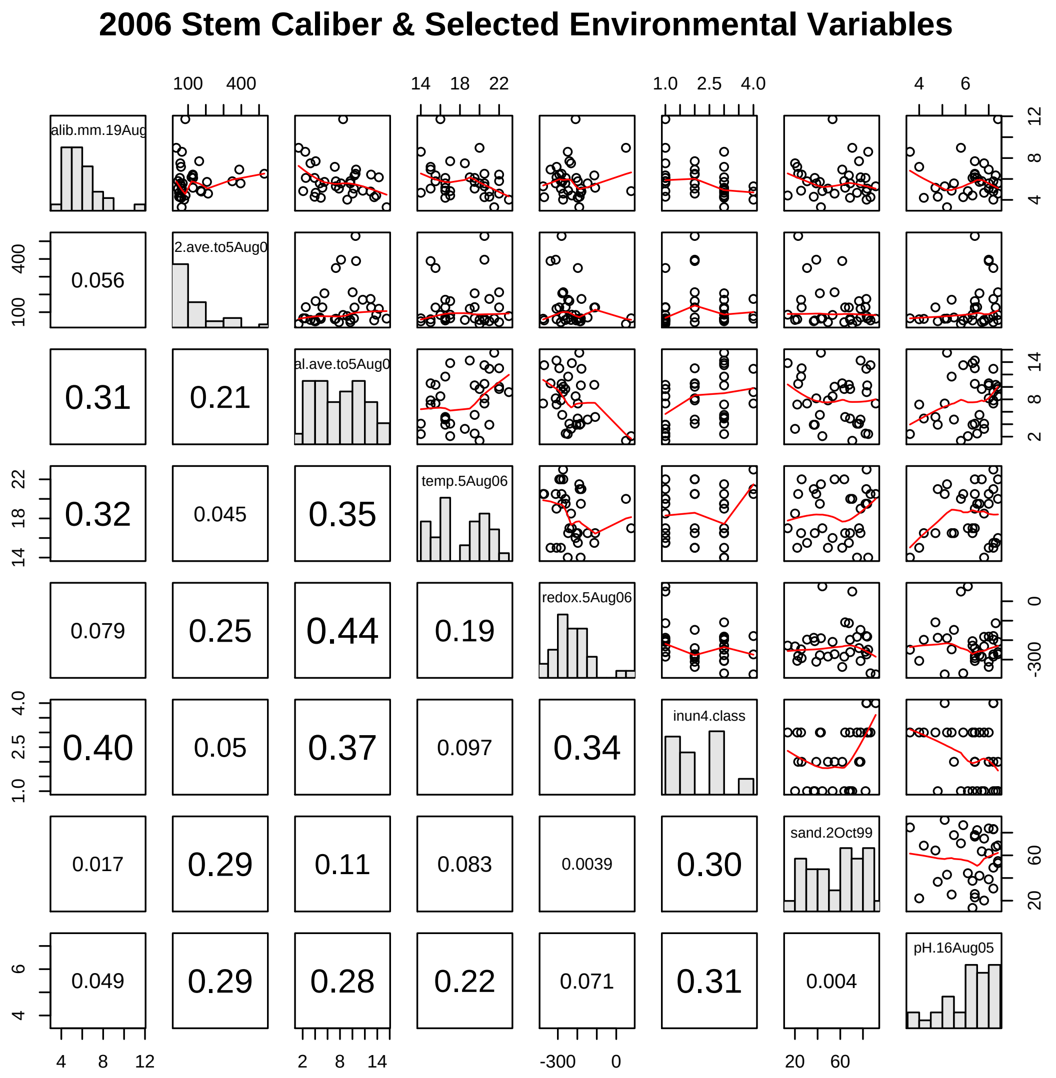


Figure 1-16. Paired plots, with lowess smoother lines, of stem caliber (19 August 2006) and selected environmental variables used in specified models, as well as histograms of these variables and Pearson correlation coefficients (+ or – direction determined visually) for all paired variables. From left to right: stem caliber (19 Aug 2006) (average of 5 tallest stems in a quadrat), average pore water sulfide concentration (20 April – 5 August 2006), average pore water salinity (21 May – 5 August 2006), pore water temperature (5 August 2006), substrate redox potential (5 August 2006), inundation class (a categorical variable based on tidal elevation zones), % sand (2 Oct 1999), and substrate pH (16 August 2005). Four quadrats were omitted from this analysis because of missing data in sulfide concentrations and/or pore water temperature: TN1-D and TN2-A vials could not be found in May, and TS1-D and TS2-D vials drained over several weeks and were empty in August. N=35.

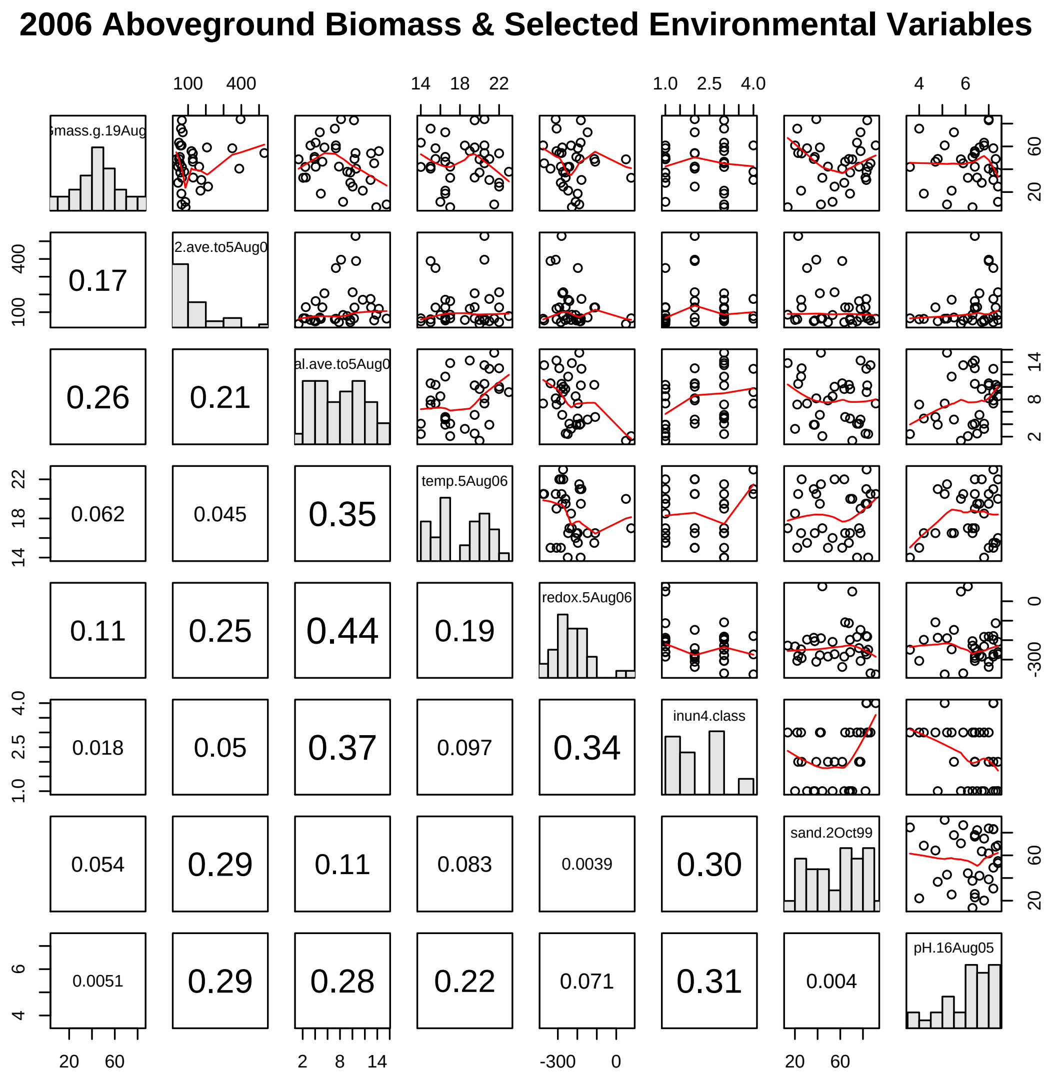
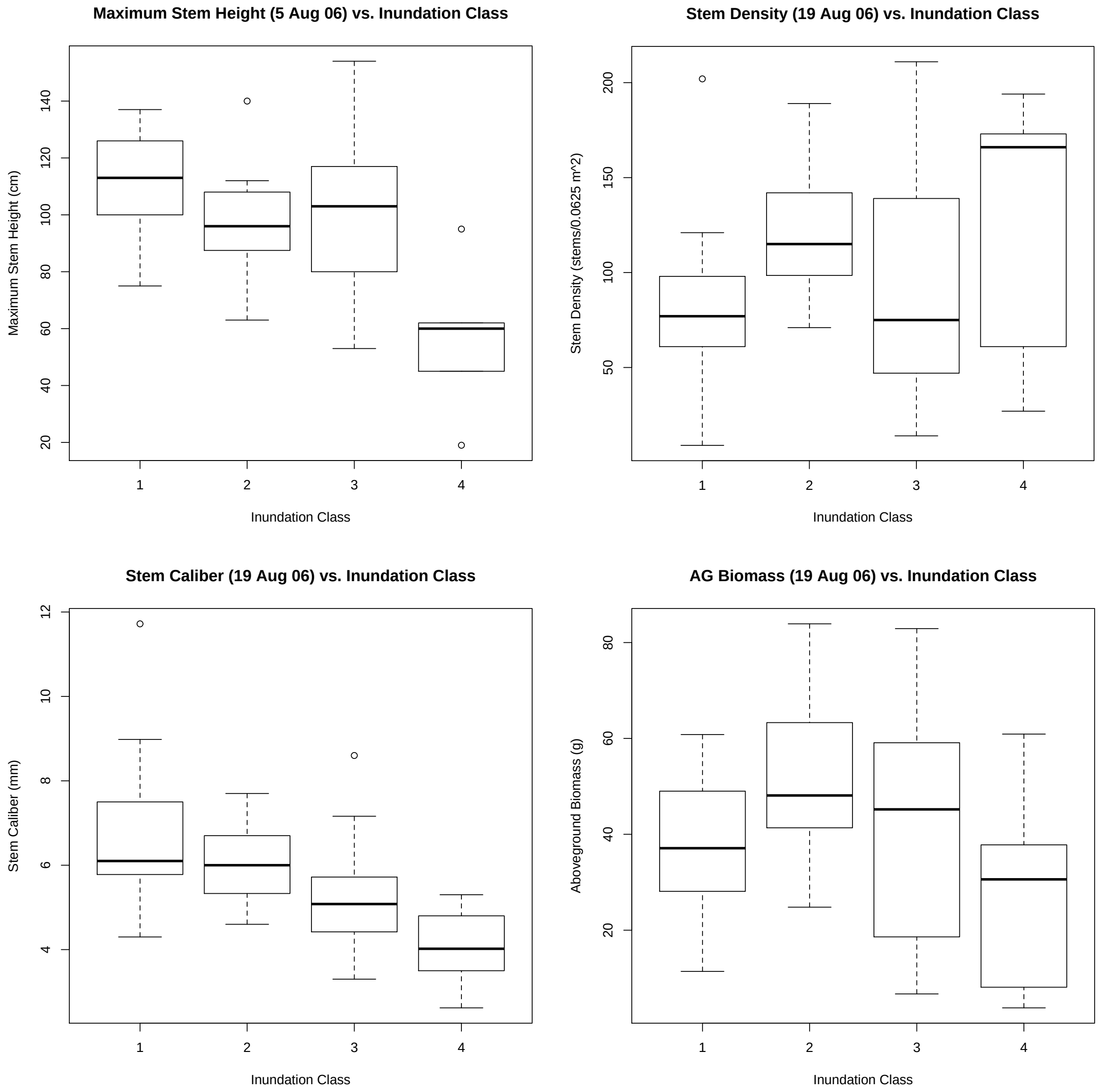


Figure 1-17. Paired plots, with lowess smoother lines, of aboveground biomass (19 August 2006) and selected environmental variables used in specified models, as well as histograms of these variables and Pearson correlation coefficients (+ or - direction determined visually) for all paired variables. From left to right: aboveground biomass (19 Aug 2006), average pore water sulfide concentration (20 April – 5 August 2006), average pore water salinity (21 May – 5 August 2006), pore water temperature (5 August 2006), substrate redox potential (5 August 2006), inundation class (a categorical variable based on tidal elevation zones), % sand (2 Oct 1999), and substrate pH (16 August 2005). Four quadrats were omitted from this analysis because of missing data in sulfide concentrations and/or pore water temperature: TN1-D and TN2-A vials could not be found in May, and TS1-D and TS2-D vials drained over several weeks and were empty in August. N=35.



Maximum Stem Height (5 Aug 06) vs. Inundation Class

Stem Density (19 Aug 06) vs. Inundation Class

Stem Caliber (19 Aug 06) vs. Inundation Class

AG Biomass (19 Aug 06) vs. Inundation Class

Figure 1-18. Plant attributes (maximum stem height (5 Aug) (cm), stem density (19 Aug) (stems/0.0625 m^2), stem caliber (19 Aug) (mm), and aboveground biomass (19 Aug) (g/0.0625 m^2)) vs. inundation class in 2006. Stem caliber was the average of 5 tallest stems in 0.0625-m^2 quadrat. Inundation class is a categorical variable and corresponded to zones across an elevation gradient in the intertidal marsh; class 1 is at the lowest and Class 4 is at the highest elevation. N=39. See Table 1-8 for ANOVA results, which were conducted for descriptive purposes.

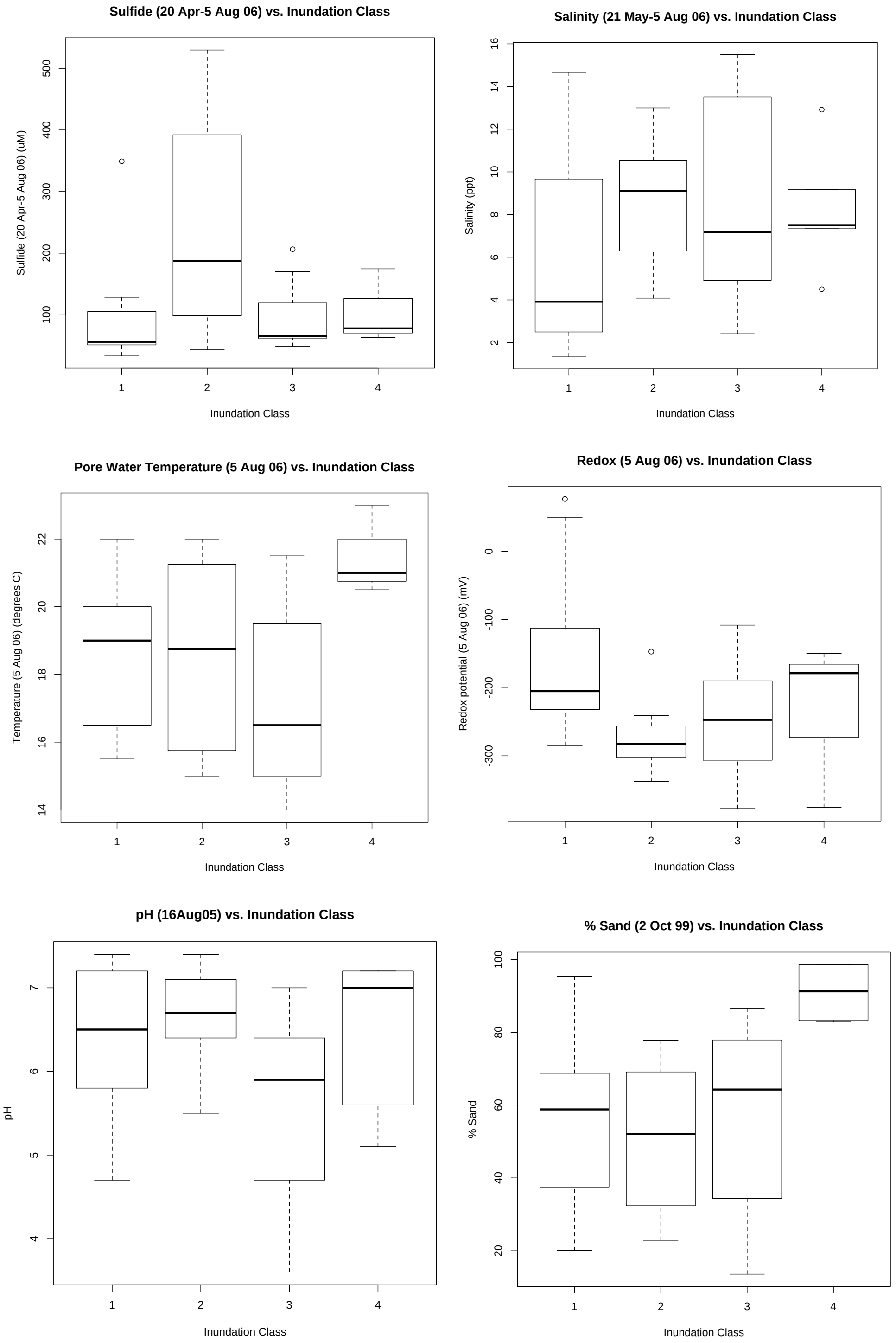


Figure 1-19. Environmental variables plotted vs. inundation class: average sulfide concentration (20 Apr – 5 Aug) (n=35), average pore water salinity (21 May - 5 Aug) (n=37), pore water temperature (n=37), substrate redox potential were measured in 2006 (n=39); substrate pH was measured in 2005 (n=39), and % sand was measured in 1999 (n=39). Inundation Class 1 was at lowest and Class 4 was at highest elevations. Sample sizes vary because of data missing for different reasons.

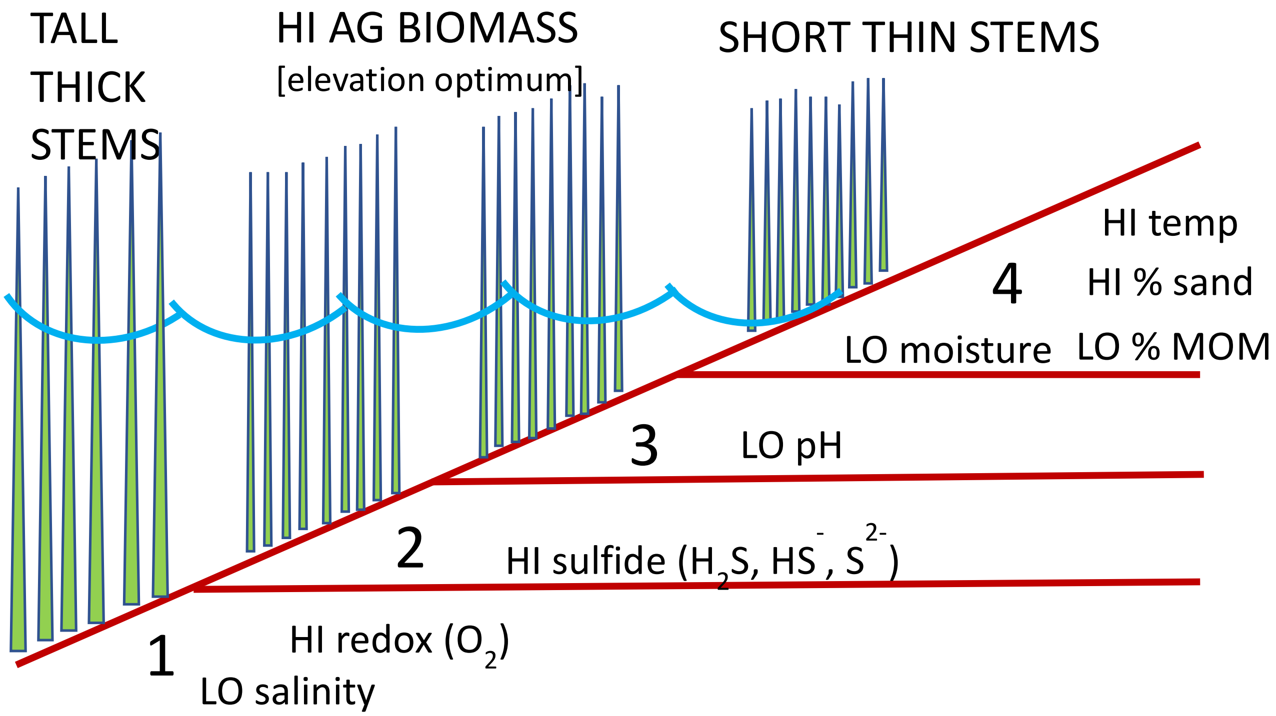


Figure 1-20. Summary of environmental conditions and plant attributes over elevation gradient in Schoenoplectus pungens stands in Grays Harbor National Wildlife Refuge, Washington. Inundation classes used in analysis are indicated with numbers. Classes 2 and 3 are characterized by high stem density and therefore high aboveground (AG) biomass. An elevation optimum appears to have shifted from Class 3 in 1999 to Class 2 in 2006.

CHAPTER 2. "Ancestors of this Grass": Toward a Sustainable Harvest of Sweetgrass (*Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith) in the Estuarine Marshes of Grays Harbor, Washington

ABSTRACT

The intertidal bulrush *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith is native to the estuarine marshes of the Pacific Northwest coast and is used by Native Americans, who call it sweetgrass, in basketry. The primary gathering ground in Western Washington is in Grays Harbor, where Grays Harbor National Wildlife Refuge has been established. Weavers from all over the state converge on this shoreline. In response to concern by some weavers that the quality of the sweetgrass was on the decline, perhaps due to overharvesting, a study was conducted to determine what, if any, effects harvest might have on the sweetgrass and, therefore, on the habitat that the U. S. Fish and Wildlife Service manages. A controlled experiment was set up using a randomized block design at four sites on the north side of the inner and outer bay. Harvest treatments were developed based on techniques learned from First Nations weavers and observed among Native Americans in the field. Intensities tested were 25% and 100% of stems harvested. The three-year duration of the study allowed us to test two frequencies of harvest: one year and two consecutive years of harvest at both frequencies. We also tested a year of rest following one year of harvest. Trampling, which is an unavoidable consequence of harvesting, was also tested at the intensity of 4 steps at every point in a plot. One and two consecutive years of trampling were tested, along with the incorporation of one year of rest into one treatment.

Two treatments, 1) two consecutive years of 100% stem harvest and 2) one year of 100% stem harvest without a year of rest, negatively affected stem height by 6.4-6.7 cm, stem density by 13.4-17.9 stems/0.0625 m^2 and AG biomass by 5.98-8.84 g. When only stems shorter than 130 cm were analyzed, the effect on height was as high as 8.2 cm. Two consecutive years of 25% stem harvest negatively affected maximum stem height and AG biomass in stands shorter than 130 cm. Trampling for two consecutive years may affect maximum stem height by 4.5 cm in stands over 70 cm. These results suggest the following guidelines for sustainable harvest: a) harvest stems of 130 cm or taller because they may not be affected by harvest; b) allow at least one year of rest after every harvest so that the plant can recover to some degree (generally, the more years of rest, the more recovery can be expected); c) harvest at the 25% level or lower to have less impact than 100% harvest and so that the plant requires less recovery time; and d) avoid trampling in the same location during two consecutive years. These guidelines could form the basis for subsequent controlled studies focused on sustainable harvest. Future studies should be conducted in collaboration with Native American and First Nations peoples. Results are compared to the very few other controlled harvest studies conducted on native species that are culturally important. Access to public lands, which often host the few remaining populations of culturally important plants, is emphasized. Recent efforts to include sweetgrass in restoration efforts are discussed.

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INTRODUCTION

Plants have played critical roles in Native American culture on the Pacific Northwest Coast for millennia, not only as sources of food, but also as fiber for physical needs (e.g., mats, garments, storage containers) and cultural expression (e.g., basketry, ceremonial objects) (Deur and Turner 2005:331). Gathering these materials was a major consideration during seasonal rounds. Harvesting techniques vary with the plant species, part of plant, culture group and individual weavers and gatherers, but include selective harvest of populations identified as high quality (Turner and Peacock 2005:103, 106-111; Anderson and Rowney 1999:233). Land management practices include using fire to increase abundance of root crops such camas (Turner and Peacock 2005:106, 126-7; Beckwith 2004:55), weaving material such as beargrass (Peter and Shebitz 2006:306), and berry-bearing shrubs such as huckleberry and blueberry (*Vaccinnium* spp.) (Turner and Peacock 2005:106, 127). Horticultural practices that maintained populations include returning seeds or cormlets to soil tilled in pursuit of root crops such as blue dicks (*Dichelostemma capitatum*), camas (*Camassia* spp.), and northern rice-root lily (*Fritillaria camschatcensis*); and returning fragments of silverweed (*Potentilla anserine*) roots and small plants to harvested intertidal plots (Anderson and Rowney 1999:233; Turner and Peacock 2005:113-4, 117; Deur 2005:308).

In some cases, particular techniques are used deliberately to minimize impact. For example, Loui (Lois) Chichinoff Thadei (Aleut) (personal communication) was taught to cut every other stem when harvesting American dunegrass (*Leymus mollis*) so that plants would continue to grow and be available for harvest the following year. Sometimes an attempt was made to alternate harvesting grounds and give an area a rest. For example, Balumna'ech Loa Ryan (Ts'msyen, formerly Tsimshian) and her daughter, *Smhayetsk* Teresa, harvested sweetgrass ((*Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith) in the Skagit River delta as a change of pace from Bowerman Basin in Grays Harbor, where they had been harvesting for years. (Unfortunately, the stems from the Skagit were too brittle to be used in weaving.) In other cases, some techniques were used to promote growth of a particular form of a plant. Southern Sierra Miwok of California burned, or when fire was prohibited, pruned or coppiced redbud (*Cercis occidentalis*) shrubs to promote growth of new branches that were "long, straight and [had] no lateral branching" and that were "slender switches with inconspicuous leaf scars, wine-red colored bark" (Anderson 1993:146-7).

Whatever the collection method and cultivation technique, the harvest must be sustainable or even promote or stimulate greater growth of desired edible parts or useable materials. Turner and Peacock (2005:145) pointed out that many of the plants on which Indigenous cultures rely in the Pacific Northwest are perennials that have the ability to regrow or regenerate tissue. More specifically, herbaceous perennials can reproduce vegetatively from underground structures that contain meristems where new stems originate. Populations of clonal organisms can thus be maintained without the aid of seeds and even when aboveground tissues are removed.

Tule (*Schoenoplectus acutus*) is one such herbaceous perennial that was used widely in the Pacific Northwest for mats, roofs and walls of summer shelters, dividers in winter houses, bedding, and canoe pads (Turner 1998:109). If 100 to 150 stems were required to make a one-square-meter mat (and most were much larger), thousands of stems would have been removed from gathering grounds each year, apparently without depletion of tule populations over time (Turner and Peacock 2005:143). Turner and Peacock (2005:145) asserted that the species' perennial habit, and ability to regenerate, is the reason that Native Americans could rely on a sustained supply of this important fiber. They also found that some gatherers believed that thinning the tule stands through harvesting resulted in better growth the following year. It is not clear whether "better" meant more stems (quantitative measurement) or more-useable stems (qualitative assessment). Removal of some stems would decrease competition for light within the stand, but the physiological mechanism for "better growth" is not readily apparent since energy storage in the form of starch build-up and translocation of nutrients from stems to overwintering structures would not occur. While cautioning readers about the potential damage that harvesting can cause, Turner (1998:16) stated that populations of herbaceous perennials such as tule and cattail were not likely to be "deplete[d] . . . to any measurable degree, since these plants tend to grow in large patches and the rootstocks will grow new stems the following year."

A close, shorter cousin of *S. acutus* is *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith (Figure 2-1). This species grows in the estuarine tidal marshes of the Pacific Northwest and is used by Native American basketweavers, who call it sweetgrass (Shebitz and Crandell 2012:162; Figures 2-2). Stems are triangular in cross-section rather than circular, as is characteristic of tule. Since sweetgrass is a clonal species with a growth form similar to tule's, the same effects of harvesting might be considered: a) harvesting may have no effect on a stand, or b) thinning may result in "better growth" in the form of taller or more useable stems the following year. Both of these outcomes would indicate sustainable harvests. A third possibility must be added because of the concern of some local weavers that sweetgrass is on the decline (Seto, personal communication).

Gathering grounds have diminished in Washington State because of habitat loss in numerous PNW estuaries and because of access that relies on automobile transportation to public lands rather than the traditional canoe (Shebitz and Crandell 2012:167; see also Chapter 3). Sweetgrass quality usually is characterized by stem length, height-to-width ratio, suppleness, and lack of spotting by decomposers (Shebitz and Crandell 2017:166). In the primary gathering ground of Bowerman Basin in Grays Harbor, the concern is that stems are shortening, the stand is shrinking, and stems are spotting (B. L. Ryan, personal communication; T. Ryan personal communication; Harradine, personal communication). So many tribes and weavers now rely on this one shoreline for sweetgrass that the stands in Bowerman Basin may be experiencing more harvesting pressure than they can withstand without negative effect (Figures 2-3 and 2-4). Overharvesting is a concern because the stands in the Skokomish River estuary were said to have been overharvested, though hydropower and agriculture may have been the primary causes for the diminished delta marsh (Nordquist and Nordquist 1983:13; see also Chapter 3).

Not only has Bowerman Basin been a gathering ground for sweetgrass since at least the 1950's (James and Martino 1986:74), but the Grays Harbor National Wildlife Refuge (GHNWR) was also established here in 1996 as part of the Nisqually National Wildlife Refuge Complex in Washington State (Grays Harbor Refuge Planning Team 1990:1; Seto, personal communication; Figures 2-5, 2-6 and 2-7). The refuge was established in this location because it provides habitat for estuarine species native to the region year-round and, most notably, hosts tens of thousands of birds migrating annually along the Pacific Flyway. Extractive uses (other than hunting) are not normally permitted on national wildlife refuges (NWR), and U. S. Fish and Wildlife Service (USFWS) prohibited sweetgrass harvesting by non-Natives at GHNWR. At the same time, in recognition of the cultural importance of the site, the agency set up a permit system for Native Americans harvesting the plant (Seto, personal communication). The permit system limits the timing of harvest to July (though this rule was later relaxed), the quantity of harvest to an armful, and the use to personal, not commercial. Some weavers adhere to this system and others do not because of decades-old established gathering practices, the relatively recent arrival of the Federal government as a land manager, the dependence of their livelihood on weaving material, and treaty rights exercised by the Quinault Indian Nation (Ryan 2000:77, 103, 110). During the process of setting up the permit system, USFWS staff learned that some weavers thought that sweetgrass was on the decline, which prompted the resource agency staff to wonder if there might be some ecological impacts from harvesting that they needed to be aware of as they carried out their mandate to preserve habitat (Seto, personal communication).

To better understand the ecological role of sweetgrass in GHNWR, USFWS funded a study that included a map of the species in the refuge that would serve as a baseline (Crandell 1999, Figure 6). Shortly thereafter, the agency funded a study that included setting up a sweetgrass monitoring program (see Chapters 1 and 3) and a harvesting experiment, which is the focus of this paper. Although the impetus for the study was the potential negative impact of harvesting on sweetgrass stands, three years of funding allowed me to design an experiment that tested several harvest regimes (in terms of frequency and intensity) in pursuit of some that were sustainable. Whether harvested in ancient times, historical times, or today, these plants need to be available year after year. Sustainable practices benefit both the weaver and the estuary.

Controlled Experiments of Harvesting

Harvesting experiments that are conducted in the field on native plants face a number of challenges and are few and far between in the literature. At the time I was setting up my experiment, Anderson and Rowney's (1999) work on blue dicks, a root food or geophyte that produces edible corms, provided the best model of a controlled study on an herbaceous species with multiple harvest regimes that mimicked different practices carried out by Native American gatherers. The study was carried out at an experimental station in California. The authors found that "harvesting at 100% intensity, through digging up all plants and corms, and without replanting cormlets at the seed stage, significantly reduced numbers of corms and cormlets compared to the controls (no harvest)" (Anderson and Rowney 1999:231). By contrast, a reduction of the harvesting intensity to 50% at the flowering or seed stages did not have a significant effect on corm or cormlet production. In other words, the latter regime appeared to be a sustainable approach to harvesting this important food source. However, this study tested one but not consecutive years of harvest, and the authors called for additional studies of longer duration and on other species (Anderson and Rowney 1999:238-9).

Anderson (1993) had earlier conducted field experiments on redbud (*Cercis occidentalis*), a shrub that sends out straight, unbranched new stems with red bark (i.e., epicormic branching) when burned. These branches are used in nearly all forms of basketry by the Miwok and other tribes throughout California. Since the prohibition on the use of fire on public lands, the Miwok have adapted by inducing the production of new branches by coppicing (or cutting trunks within several inches of the ground) or pruning the shrubs. This study tested coppicing of shrubs for one and two years and measured the plant response in terms of the height and number of new stems and number of useable stems. Anderson (1993:156-8) found that both treatments resulted in significantly more useable stems than the uncut control group. Her interpretation was that coppicing could serve as a technique that would promote useable shoots without negative effects. An appropriate caveat here would be that the focus was on the portion of the plant that weavers use, rather than on the life cycle of the shrub. The study does report that shrub height was significantly lower in treated shrubs compared to the uncut control group. The caveat offered by the author is that more information was needed about effects of multiple years of coppicing, with particular concern about the potential for killing the shrub at some point (Anderson 1993:160). The difficulty of conducting controlled studies in the field was noted in the variability not only of plant state and characteristics, which required transformation of some of the data, but also of the environmental conditions, such as shade, experienced by individual shrubs and different sites. A final constraint was acknowledged: the effect of coppicing on redbud may be different from burning, especially given the fact that the shrub is adapted to fire through epicormic branching as well as increased germination resulting from fire-aided cracking of the seed coat (Anderson 1993:161).

Beckwith (2004) conducted a study to test effects of simulated harvesting treatments on camas populations in parkland areas near Victoria, British Columbia. The appeal of this study was the fact that treatments were applied to naturally occurring populations. The challenges appear to have been site variability and small sample size. Harvesting treatment consisted of removal of the largest bulbs in a single year, and one treatment consisted of harvesting and burning combined. Unlike Anderson and Rowney's

(1999) geophyte study, the response variables in this study were aboveground attributes of the plant (e.g., leaf number, flowering plants), rather than the edible portion of the plant, so the effect of harvesting on production of more harvestable bulbs is not directly captured. However, the author stated that regular flowering was the best aboveground indicator of large bulbs, so that may serve as a surrogate response variable. For *Camassia leichtlinii* only, harvesting and burning treatments (alone and in combination) resulted in a significant decrease in leaf number and flowering plants compared to the control three years after treatments were applied. No treatment effect was found for *Camassia quamash* (Beckwith 2004:147-9, 152-3, 155), but as noted earlier, not detecting treatment effects can be a function of large variances and small sample size. The experimental design in this study is not entirely clear, but it appears that four treatments (including control) were applied to forty plots (ten of each treatment) established across four sites. Blocks of treatments (i.e., one of each treatment plus control) were described but not included as a factor in the analysis (Beckwith 2004:133, 147-9). A randomized block design is often used in field studies to address variation across the landscape (see next example and Methods section). In addition, sampling units should be the 1-meter by 1-meter plots to which treatments were applied, which means that n=1 (one independent unit per treatment) at one site and n=2 at another. I have not been able to determine how these sites could be analyzed in the statistical model (and produce a mean and variance) unless individual plants were used as the independent unit for analysis. With respect to the question of sustainability, we cannot conclude with confidence that the experimental harvest (with or without burning) represents a sustainable regime for *C. quamash*, and the evidence suggests that it is not sustainable at the three-year mark for *C. leichtlini*. As Beckwith

(2004:162) notes, "many more questions were generated from this research than were answered."

The most recent controlled study was conducted by Cullis-Suzuki et al. (2015) on eelgrass in existing beds in the Gulf Islands, British Columbia. The sweet rhizomes were traditionally gathered in springtime, a welcome change from the dried foods of winter (Cullis-Suzuki et al. 2015:27). Traditional harvesting techniques used by the Kwakwaka'wakw were thoroughly researched with knowledge holders, and a protocol was developed for the controlled study. Elders stated that harvesting of the eelgrass meadows should result in larger rhizomes. A complete randomized block design was used for the application of three harvest treatments of 30%, 50% and 100% removal of stem and attached rhizome (Cullis-Suzuki et al. 2015:27). The logistics involved subtidal work with SCUBA gear, an indication of the commitment to an *in situ* study. Harvesting intensity had a statistically significant positive effect on shoot regeneration, compared to the control but treatments did not differ from each other. Additional analysis of shoots removed and shoot regeneration revealed that the optimum harvesting intensity was 35% (Cullis-Suzuki et al. 2015:31). Percent stem and rhizome removal also had a biologically meaningful, if not statistically significant (p=0.069), positive effect on rhizome size measured as volume. The small sample size limited the power of the experiment, but this study provides support for the sustainability of traditional practices and possibly the increase in rhizome size following harvest. In a later study, a simpler methodology that could be more readily replicated was implemented at low tide. A single treatment of 30% stem and rhizome removal was used because it most closely mimicked the intensity of harvest accomplished with the traditional twisting stick (Cullis-Suzuki et al. 2015:33). Although the modified method was described and the feasibility of larger sample sizes was noted, no results for that study were reported in this paper. Notably, neither methodology tested multiple years of harvest.

To understand the sustainability of harvesting practices on native species, more controlled experiments conducted *in situ* or in field conditions are needed. This survey of the literature makes several challenges clear and suggests several guidelines: site and patch variability require larger sample sizes than have been employed thus far; randomized block designs can increase our ability to tease apart treatment and landscape effects; simple experimental designs allow for more replication (i.e., larger sample sizes) and therefore greater power of statistical analysis; and multiple-year studies are needed to assess the overall sustainability of repeated harvest.

Studies of Trampling by Humans

As gatherers work their way through sweetgrass stands at GHNWR, trampling of vegetation is unavoidable (personal observation). Trails of crushed and dying stems combined with bare substrate become visible relatively quickly, and by season's end, the network of brown paths within the green stands is visible in aerial photography. However, the following year's growth does not exhibit "shadows" of those paths, so it is not clear what if any impact trampling has during harvesting.

A number of studies have focused on the effects of human trampling on vegetation. Burden and Randerson (1972:453) studied human trampling in semi-natural areas in Great Britain. They determined that grass species in general were resistant trampling, but some grass species were more resistant to heavy trampling than others. In a study conducted in

Costa Rica, Frenkel (1972:87, 88) described convergent vegetation in habitats modified by human trampling. He speculated that trampled environments are a kind of extreme environment and drew a connection to the stresses of wetlands: "Many species adapted to trampled situations likewise occupy the flooded margins of streams and lakes where soil pore space is also diminished in these seasonally inundated habitats" (Frenkel 1972:88).

Andersen (1995:223) looked at human trampling in five plant communities, including a salt marsh, on the coast of the Baltic Sea in Denmark. Comparisons were made between existing paths visited by 10 visitors per day and the vegetation surrounding the path. This approach does not require manipulation and detects changes that have already occurred over time. The salt marsh in this study was dominated by graminoids in one characterization and, in another, by geophytes (i.e., perennials with overwintering or regenerating buds, such as rhizomes, well below surface of soil) and hemicryptophytes (i.e., perennials with overwintering or regenerating buds at ground level or within the top layer of the soil) (Andersen 1995:227). Most of the salt marsh species were deemed "indifferent" to trampling, and Andersen (1995:223, 228) found that salt marsh was the most resistant vegetation of the five communities.

Consistent with this work was a study by Cole (1995) in eighteen vegetation types in five different mountain regions in the United States. Experimental trampling lanes were delineated in existing vegetation and subjected to 0, 25, 75, 200 or 500 one-way walking passes (Cole 1995:216). Plant responses were measured two weeks and then 1 year after trampling. Response to trampling was explained more by morphological characteristics than the site characteristics such as altitude and vegetation structure or layers (Cole:1995:215). The most resistant species were tufted or matted graminoids.

In an unusual subtidal study, Eckrich and Holmquist (2000) studied human trampling in seagrass (*Thalassia testudinum*) beds located below along shorelines in Puerto Rico that are popular for wading. Although this species is rhizomatous and might be expected to withstand this kind of disturbance, it did not evolve with trampling by humans, ungulates, or livestock. The authors wondered if environmental factors, such as substrate or seasonal timing, might explain the plant's response more than growth form (Eckrich and Holmquist 2000:199, 200). Their treatment plots were trampled 20 and 50 times per month. Standing biomass and other plant characteristics were significantly decreased by light and especially heavy trampling as of four months after treatment. Rhizomes were significantly decreased after heavy trampling, especially in soft substrate. Some recovery occurred in the following months, but leaf-area index and short-shoot density were still significantly lower than controls at seven months. Fourteen months after the application of treatments, differences between the experimental plots and the surrounding vegetation were still visible. Of the rhizomatous species reviewed here, seagrass was the most sensitive and had the longest recovery time. Eckrich and Holmquist (2000:206) speculate that lack of sclerenchyma tissue, which helps terrestrial grasses resist breakage and tolerate ungulate trampling, may explain the impacts to *Thalassia*. This sensitivity and slow recovery period led the authors to recommend non-wading water activities or wading only on firmer substrates in at least 1 meter of water in a concentrated area (Eckrich and Holmquist 2000: 203, 204 207).

These studies suggest that *S. pungens*, as a graminoid and geophyte (or hemicryptophyte), may well be resistant to or resilient following human trampling. Because of its long use in basketry in the Pacific Northwest, the trampling is not new, though use of canoes may have helped gatherers avoid trampling before the early 1900's (see Chapter 3). As an emergent wetland plant that is not buoyed by water much of the day during the growing season, its tissues are not as soft as those of seagrass and stems must be stiff enough to hold themselves erect. Given the dynamic environment in which the species thrives, trampling may be a small disturbance relative to other factors affecting sweetgrass growth. The fact that trampling intensity was generally much greater in these studies than was estimated in the GHNWR marsh strengthens that argument.

Need for Field Research

Parallel to the need for a sustainable harvest study is a call within a corner of the ethnobotanical literature for field experimentation, especially long-term studies, on plant harvest (M. K. Anderson 1996:231, 239). Anderson's own ethnobotanical work is unusual in that she goes beyond description of plant collection and land management to conduct structured experiments (contrast also P. J. Anderson's (2004) focus on socio-economic context). A manual of ethnobotanical methods focused on survey techniques and contained only a passing reference to revisiting trees – and no reference to herbaceous species – in order to determine impacts of cultural practices (Martin 2004:163). Referring to traditional landscape management techniques that promoted growth of desirable plants or plant forms, Deur and Turner (2005:340) encouraged "experimental monitoring and monitored replication." More recently, some controlled experiments have been conducted with land-management practices. Shebitz and others (Shebitz 2006; Shebitz, Reichard and Dunwiddie 2009) conducted experiments to determine the effects of the use of fire on beargrass (*Xerophyllum tenax*). Studies that directly manipulate the plants and determine effects on the scale of a plant are rare. Anderson and Rowney's (1999) work is among few examples I have been able to find. They considered their results preliminary in part because the study examined effects of a single year's harvest, and they called for multi-year studies that included some repeated harvesting. Multi-year studies can also address rotation of harvest locations, or incorporating rest into a regime. Turner and Peacock (2005:146) stated that this approach was one way that "productivity of these [root and berry] habitats was ensured," sometimes in combination with burning. Rest is potentially a dimension of sweetgrass harvest that would aid sustainability. It may well have in the past if not deliberately then in a self-regulating way insofar as gatherers would have been able to survey stands while approaching them from the water side in their canoes and target the most desirable portions of the stands. Those most desirable patches may have had the time to recover from some past harvest.

Sweetgrass Study

In response to the need for understanding sustainability and for executing a controlled multi-year experiment, this sweetgrass study was conducted at GHNWR and neighboring sites. It addresses concerns held by several parties with potentially competing needs. It is structured as a controlled experiment that directly manipulates plants and is a multi-year study that tests harvesting regimes that include two consecutive years of harvesting and, in other cases, some rest. It was implemented at multiple sites so that we would be able to generalize the findings to the broad distribution of sweetgrass as opposed to limiting inferences to GHNWR.

Null hypotheses tested were that plant attributes (stem height, stem density, stem caliber, and aboveground (AG) biomass) are not statistically significant among harvest and trampling treatments. If a harvest treatment is not significantly different from the control, it has the potential to be a sustainable regime.

STUDY AREA

The study region was Grays Harbor estuary in Washington (Figure 2-5). Grays Harbor is a classic drowned river mouth estuary where the Chehalis River meets the Pacific Ocean. All sweetgrass locations documented by the Washington State Department of Natural Resources (DNR) (Dethier 1990) and by the Corps of Engineers (Smith et al. 1976) were visited by foot, kayak or motorboat. Sweetgrass stands were confirmed in all areas, and study sites for this harvesting experiment were located in the areas of the most extensive stands of sweetgrass, which were found at the Grays Harbor National Wildlife Refuge (locally known as Bowerman Basin), Chenois Creek, Grass Creek, and Point New (Figure 2-6 and 2-7). (Point New was dropped after access was limited due to property ownership, and a portion of the Grass Creek site was dropped as a result of access limited by tidal conditions at a headland.) These shorelines are all located on the western shores of the northern part of the bay and the northern shore of the inner bay, both of which experience greater exposure to wind and wave energy than other shorelines within the bay, which is consistent with the Dethier's (1990:33, 35) use of *S. pungens* as a diagnostic species of estuarine intertidal sand or mixed-fine and mud sites (i.e., partly enclosed, eulittoral, mesohaline marsh). *S. pungens* is also found at other locations throughout Grays Harbor, but these other populations are small and do not lend themselves to harvesting.

Bowerman Basin is a manmade basin created by the construction of an airport strip (initially a World War II military air base) where the mudflats meet a deeper channel on the northern side of the inner bay. Additional fill between the shoreline and the airport causeway occurred with the deposition of plentiful sediments dredged from the commercial channels within the harbor (see Chapter 3).

METHODS

Harvesting Technique

Information about harvesting was gathered from the following sources: anthropological literature (Turner et al. 1983; Thompson and Marr 1983; see additional references in Shebitz and Crandell 2012); reports from the U.S. Fish and Wildlife staff that manage the wildlife refuge; personal observations of patterns in harvested stands; personal observations of harvesters at work; conversations with some gatherers on site (Florine Berg-Shale, personal communication; Lois Chichinoff Thadei, personal communication); observations of areas during harvesting season; and training by two Ts'msyen (Tsimshian) weavers (T. Ryan and B. L. Ryan, personal communication). Experimental treatments were developed to mimic techniques used by gatherers. The traditional pulling technique was used for the tests of harvesting intensity and frequency (Figure 2-4).

Treatments Used in Randomized Block Design

The harvesting experiment was set up using a randomized block design in order to be able to account for landscape variation within a particular site (Tables 2-1 and 2-2). Blocks in *S. pungens* stands taller than 70 cm and of uniform height were located at four sites in Grays Harbor: stands on the north and the south shores of the GHNWR, stands near the mouth of Grass Creek, and stands near the mouth of Chenois Creek. All observed harvesting had occurred in stands higher than 70 cm, so blocks were located in stands with maximum height at least that tall. All sites were located on the northern shore of Grays Harbor and had western or southern exposure to wind and wave energy, the conditions under which *S. pungens* is expected to be a dominant species in the marsh community (Dethier 1990:33, 35). These were also the conditions under which extensive stands of the species had been found in bay-wide surveys of Grays Harbor shorelines (personal observation).

Further, in GHNWR, blocks were established near existing transects (see Chapter 1) but far enough away from sporadic human activity (e.g., social trails, informal entry points, boardwalks) in order to minimize the possibility of disruption of study. Areas in which sweetgrass stems had lodged were also avoided.

Blocks were established parallel to the shoreline (i.e., at constant elevation). At three sites, they measured 2 m wide by 6 m long. At one site (north shore of GHNWR), they were 2 m wide by 8 m long in order to accommodate an extra harvesting treatment (50% harvest, which were not analyzed in this study because so much biomass was removed that the plots resembled the 100-percent plots). Blocks were divided into plots measuring 1 m by 1 m, and treatments were randomly assigned to them. Treatments addressed harvesting intensity, harvesting frequency, and trampling frequency. Treatments were applied to an entire square meter, but data was collected from the center of each plot to minimize edge effects.

Experimental treatments were developed to mimic traditional harvesting practices. Stems were pulled, not cut, so the stem separated from the belowground rhizome with a "pop." Many weavers harvest all stems in a patch that is roughly 1 meter in diameter (personal observation). This approach was mimicked by removing 100 percent of stems in an experimental plot. Other weavers harvest stems selectively, and this approach was mimicked by removing 25 percent of stems.

Harvesting intensity was tested by removing 25 or 100 percent of stems using the traditional pulling technique. In 25-percent harvest plots, stem density was estimated by counting stems in a 25 cm-by-25 cm quadrat near the center of the plot and multiplying by 16 to approximate the density in the full square meter plot. The plot was divided into quarters with guide rods, and the same number of stems were removed from each quarter. Tallest stems were preferentially removed in order to mimic selective harvesting which favors taller stems (personal observation).

Harvesting frequency was tested by harvesting each intensity-level for one year – either the first or the second year of the study – or two consecutive years. The three-year duration of the study allowed us to address the role of rest, or rotation, in harvest practices. Rotation of harvest areas (i.e., harvest one year, let stand rest the next) was mimicked by the treatment that involved one year of harvesting during the first year of the study followed by one year of rest. Two consecutive years of harvesting mimicked harvesting without rest, a practice that might be the most direct route to potential overharvesting. Harvesting only the second year revealed the initial response of sweetgrass to harvest.

Trampling was tested at a single intensity level: a total of four steps during the peak growing season on every part of the plot. Twice during the growing season, two steps were applied in every part of the plot by a 170-pound person in men's size 7 LaCrosse rubber boots during the growing season between 1 August and 8 September 2000 and between 11 August and 13 September 2001 (or 4 to 6 weeks apart), except at the Grass Creek stands where the complete trampling treatment occurred during one visit (6 September 2000 and 12 September 2001) due to access limitations. The total treatment of 4 steps was based on the pattern of paths observed in the most intensively harvested area in GHNWR in 1999.

The tree-like pattern of trails fanning out from the trailhead, with each trail terminus representing one harvesting foray, suggested that a particular path would have been walked over an average of 16 times. Given normal human strides in a marsh, a given point on the ground would have been directly trampled a small portion of the number of times the path was traveled/walked over.

The following treatments were applied during the first and second years as follows:

1) H1-1-25 - Harvested 25% stems for one year, the first year
2) H1-2-25 - Harvested 25% stems for one year, the second year
3) H2-25 - Harvested 25% stems for two consecutive years
4) H1-1-100 - Harvested 100% stems for one year, the first year
5) H1-2-100 - Harvested 100% stems for one year, the second year
6) H2-100 - Harvested 100% stems for two consecutive years
7) T1-1 - Trampled 4 times for one year, the first year
8) T1-2 – Trampled 4 times for one year, the second year
9) T2 - Trampled 4 times for two consecutive years
10) C3 - Control measured Year 3

A concise list of treatment abbreviations is presented in Table 2-1.

In the third year of the study, a control plot and all treatment plots were sampled using a 25-cm by 25-cm quadrat placed in the middle of each plot. Maximum stem height (cm), stem density, stem caliber of the 5 tallest stems were measured. To measure aboveground (AG) biomass, stems were cut at the ground level, washed in the lab, and dried in an oven at 70 ^{o}C for 48 hours. Belowground biomass (BG) samples were collected on the north and south shores of the wildlife refuge only. A PVC core that was 22 cm in diameter and 15 cm long was pounded into the substrate. All root and rhizome material and substrate were scooped out of the core. Washing of these samples began in the field and was completed in the lab. Tissue was separated into live and dead portions based on color, firmness, and translucence. Washed BG biomass was dried as described for the AG biomass.

In order to assess the possible contribution of dead biomass to final AG biomass measurements, dead AG biomass was separated from live biomass in samples from the north and south shores within the wildlife refuge. The separation occurred after initial drying, so buff color and shriveling were used as the criteria for dead stems. Dead biomass was subtracted from total AG biomass and analysis was conducted on both portions.

Statistical Methods

The harvest and trampling experiment were analyzed as split-plot designs (Gard 2010; Tear, personal communication). All plant attribute data was transformed using natural log to improve normality (Gard 2008, Table 2-3). The R statistical program (The R Foundation for Statistical Computing, 2012; Version 2.15.0 (2012-03-30)) was used to conduct analysis of variance (ANOVA) on the model attribute ~ treatment + site + Error(block). Block was treated as a random factor so that inferences could be drawn to all possible blocks rather than only those in the study (Gard 2008; Tear, personal communication). Harvest and trampling treatments were analyzed together, as implemented in the field, as well as separately since post-hoc comparisons of treatments were most logical within harvest or trampling groups. When all treatments were analyzed together, treatment had 9 degrees of freedom. When harvest treatments were analyzed separately, treatment had 6 degrees of freedom. When trampling treatments were analyzed separately, treatment had 3 degrees of freedom.

Post-hoc analyses included Tukey Honestly Significantly Different (Tukey HSD) tests among all treatments and Dunnett's test against the reference control. Tukey HSD tests were conducted with R using the model *attribute ~ treatment + site/block*, with the factor block nested within site. Dunnett's tests were conducted with IBM SPSS Statistics (Version 19.0.0), using the model *attribute ~ treatment + site + site/block*, which nested block within site and provided the correct error structure for tests (Tear, personal communication).

All ANOVA's and post-hoc tests were also conducted without blocks BN1 and BN2, where stem heights were especially tall (Gard 2008).

RESULTS

In the controlled harvest experiment, which included trampling treatments, significant differences were found for maximum height, aboveground biomass, and stem density, but not stem caliber when natural log values were compared. No significant differences among treatments were found for belowground biomass, dead stems and dead aboveground biomass, which were measured only within the wildlife refuge, on the north and south shores.

The following descriptions of results are organized by plant attribute and treatment. Results are generally presented as negative effects of a treatment on a given plant attribute. Assessment of sustainability of harvest regimes based on non-significant differences (i.e., no effect) are addressed in the Discussion. A summary of quantified effects is presented in the last section.

Maximum Stem Height

Treatment had a statistically significant effect on log maximum stem height when all treatments were analyzed together using ANOVA (p=0.0152) (Table 2-4, Figure 2-8). However, when harvest and trampling treatments were analyzed separately, the effect on maximum stem height remained statistically significant for harvest (p=0.0499) but not for trampling (p=0.194) (Table-2-4).

Tukey HSD test was used to determine which pairwise comparisons were significantly different for maximum stem height (Table 2-5). When maximum stem heights of all treatments were analyzed together, the following pairwise comparisons were found to be significantly different: trampling one year (second year only/with no rest) was taller than 100% stem harvest one year (second year only/with no rest) (4.630 ± 0.1485 vs. 4.548 ± 0.2250, p=0.0478; 103.6 ± 16.0 g vs. 97.1 ± 26.4 g, untransformed).

When exceptionally tall blocks (outliers BN1 and BN2 were more than 2 standard deviations from the transformed mean, see Figures 2-8 and 2-9) were removed from the analysis, the following significant differences in maximum stem height were found: the control plots were taller than plots with one year of 100% harvest (second year only/with no rest) (4.582 ± 0.1230 vs. 4.494 ± 0.1327, p=0.0342; 98.4 ± 12.3 cm vs. 92.1 ± 13.6 cm, untransformed); trampling for one year (second year only/with no rest) was taller than both 100% stem harvest for two consecutive years (4.601 ± 0.1149 vs. 4.512 ± 0.1451, p=0.0307; 100.2 ± 11.1 cm vs. 92.1 ± 13.6 cm, untransformed) and 25% stem harvest for two consecutive years (4.601 ± 0.1149 vs. 4.513 ± 0.1242, p=0.0356; 100.2 ± 11.1 cm vs. 91.9 ± 11.5 cm, untransformed) (Table 2-4, Figure 2-10).

When harvest treatments were analyzed separately using the Tukey HSD test, the control was taller than 100% stem harvest for one year (second year only/with no rest), though this difference was just barely not statistically significant at the α=0.05 level (4.624 ± 0.1858 vs. 4.548 ± 0.2250, p=0.0582; 103.8 ± 21.6 cm vs. 97.1 ± 26.4 cm, untransformed) (Table 2-5).

When trampling treatments were analyzed separately using ANOVA and outlier blocks (BN1 and BN2) were removed, treatment was not found to have a significant effect (p=0.104) (Table 2-4). However, when Tukey HSD test was performed, stems in plots trampled for one year (second year only/with no rest) were found to be taller than those trampled for two consecutive years, though the difference was not significant at the 0.05

level (4.601 ± 0.1149 vs. 4.539 ± 0.1255, $p=0.0777$; 100.2 ± 11.1 cm vs. 94.3 ± 11.5 cm, untransformed) (Table 2-5).

When Dunnett's test was used to compare treatments to the control (i.e., no harvest or trampling), maximum stem height in the following treatments was significantly less than the control (4.624 ± 0.1858; 103.8 ± 21.6 cm, untransformed): 100% harvest for one year (second year only/with no rest) (4.548 ± 0.2250, $p=0.012$; 97.1 ± 26.4 cm, untransformed); and 100% stem harvest for two consecutive years (4.557 ± 0.2056, $p=0.030$) (Table 2-6). When Dunnett's test was performed after BN1 and BN2 were removed from the dataset, those two treatments remained significantly different from the control; and an additional treatment (25% stem harvest for two consecutive years) was found to be significantly shorter than the control (4.513 ± 0.1242, $p=0.035$; 91.9 ± 11.5 cm, untranformed). When trampling treatments were analyzed separately using Dunnett's test on all blocks, stems in plots trampled for two years were shorter than those in the control plots, but the difference was not statistically significant at the $\alpha=0.05$ level (4.581 ± 0.1855; 99.3 ± 20.4 cm, untransformed).

Stem Density

Treatment had a statistically significant effect on natural log stem density when all treatments were analyzed together ($p<0.0001$) (Table 2-7, Figure 2-11). However, when harvest and trampling treatments were analyzed separately, the effect on stem density remained statistically significant for harvest ($p=0.0004$) but not for trampling ($p=0.279$). So all trampling treatments did not affect stem density.

Post-hoc analysis with the Tukey HSD test found the following stem-density differences that were significant at the $\alpha=0.05$ level: Control plots were more dense than 100% stem harvest one year without rest (4.374 ± 0.5939 vs. 3.976 ± 0.9448, p=0.0044; 92.4 ± 49.3 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed); plots subjected to trampling one year without rest were more dense than those with 100% stem harvest for one year without rest (4.307 ± 0.6220 vs. 3.976 ± 0.9448, p=0.0409; 89.0 ± 54.8 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed); plots subjected to 25% stem harvest for two consecutive years were more dense than those subjected to 100% stem harvest for one year without rest (4.317 ± 0.6679 vs. 3.976 ± 0.9448, p=0.0297; 90.4 ± 53.5 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed); plots subjected to 25% stem harvest for one year followed by one year rest were more dense than plots subjected to 100% stem harvest for one year without rest (4.335 ± 0.7061 vs. 3.976 ± 0.9448, p=0.0168; 92.8 ± 51.7 vs. 74.5 ± 53.5 stems/0.0625 m2, untransformed); plots trampled for one year followed by one year rest were more dense than those subjected to 100% stem harvest for one year without rest (4.434 ± 0.5754 vs. 3.976 ± 0.9448, p=0.0004; 96.9 ± 47.8 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed); control plots were denser than those subjected to 100% stem harvest for two consecutive years (4.374 ± 0.5939 vs. 4.046 ± 0.9175, p=0.0443; 92.4 ± 49.3 vs. 79.0 ± 55.0 stems/0.0625 m^2, untransformed); and plots trampled for one year followed by one year rest were denser than those subjected to 100% stem harvest for two consecutive years (4.434 ± 0.5754 vs. 4.046 ± 0.9175, p=0.0063; 96.9 ± 47.8 vs. 79.0 ± 55.0 stems/0.0625 m^2, untransformed) (Table 2-8, Figure 2-12).

When harvest treatments were analyzed separately from trampling treatments, the following additional comparisons were found to be significantly different: 25% stem harvest for one year without rest resulted in greater stem density than 100% stem harvest for one year without rest (4.290 ± 0.5323 vs. 3.976 ± 0.9448, p=0.0432; 83.1 ± 42.5 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed); control plots were denser than those subjected to 100% stem harvest for two consecutive years (4.374 ± 0.5939 vs. 4.046 ± 0.9175, p=0.0296; 92.4 ± 49.3 vs. 79.0 ± 55.0 stems/0.0625 m^2, untransformed) (Table 2-8).

Plots subjected to 25% stem harvest for one year without rest were more dense than those subjected to 100% stem harvest for one year without rest, but this difference was not significant (4.290 ± 0.5323 vs. 3.976 ± 0.9448, p=0.0653; 83.1 ± 42.5 vs. 74.5 ± 53.5 stems/0.0625 m^2, untransformed) (Table 2-8). Similarly, plots subjected to 25% stem harvest for one year followed by one year of rest were more dense than plots subjected to 100% stem harvest for two consecutive years, but the difference was not significant (4.335 ± 0.7061 vs. 4.046 ± 0.9175, p=0.0828; 92.8 ± 51.7 vs. 79.0 ± 55.0 stems/0.0625 m^2, untransformed).

Dunnett's test comparing treatments to the control (4.374 ± 0.5939; 92.4 ± 49.3 stems/0.0625 m^2, untransformed) resulted in the following significant differences: the control was denser than 100% stem harvest for one year without rest (3.976 ± 0.9448, p<0.001; 74.5 ± 53.5 stems/0.0625 m^2, untransformed), as well as 100% stem harvest for two consecutive years (4.046 ± 0.9175, p=0.005; 79.0 ± 55.0 stems/0.0625 m^2, untransformed) (Table 2-6).

Aboveground Biomass

Natural log aboveground (AG) biomass was found to differ significantly among treatments (p=4.66e-06) (Table 2-9, Figure 2-11). When harvesting treatments were analyzed separately from trampling treatments (but compared to the same control), AG biomass in harvesting treatments was significantly different from the control (p=0.0006), but AG biomass subjected to trampling treatments was not found to differ significantly from the control (p=0.326).

Tukey Honestly Significantly Different (HSD) test was used to determine which pairwise comparisons were significantly different (Table 2-9, Figure 2-13). When all treatments were analyzed together, the following pairwise comparisons were significantly different for AG biomass: The control was greater than harvesting for the second year only (3.497 ± 0.5575 vs. 3.087 ± 0.8199, p=0.0015; 37.82 ± 19.05 g vs. 28.98 ± 20.67 g, untranformed data). Trampling for the second year only was greater than harvesting 100% stems for two consecutive years (3.481 ± 0.5603 vs. 3.214 ± 0.7572, p=0.0029; 37.81 ± 21.37 g vs. 31.84 ± 21.02 g, untransformed). Harvesting 25% of stems followed by one year of rest resulted in greater AG biomass than harvesting 100% of stems followed by one year of rest (3.442 ± 0.5834 vs. 3.366 ± 0.6082, p=0.0124; 35.95 ± 17.76 g vs. 34.38 ± 21.07 g, untransformed). AG biomass in plots trampled for one year followed by a year of rest was greater than in those with 100% stems harvested for one year (second year only/with no rest) (3.580 ± 0.4983 vs. 3.087 ± 0.8199, p<0.001; 40.13 ± 18.55 g vs. 28.98 ± 20.67 g, untransformed). Two years of trampling resulted in significantly greater AG biomass than harvest of 100% stems for one year (second year only/with no rest) (3.412 ± 0.5888 vs. 3.087 ± 0.8199, p=0.0330; 35.31 ± 18.59 g vs. 28.98 ± 20.67 g, untransformed). Trampling for one year followed by a year of rest resulted in greater AG biomass than two consecutive years of both 25% stem harvest (3.580 ± 0.4983 g vs. 3.202 ± 0.7523 g, p=0.0053; 40.13 ±

18.55 g vs. 31.43 ± 20.99 g, untransformed) and 100% stem harvest (3.580 ± 0.4983 g vs. 3.214 ± 0.7572 g, p=0.0084; 40.13 ± 18.55 g vs. 31.84 ± 21.02 g, untransformed).

When all treatments were analyzed together using Tukey HSD, the control was not found to be significantly different from two consecutive years of 25% stem harvest (p=0.0790); but when harvest treatments were analyzed separately, the p-value dropped (3.497 ± 0.5575 g vs. 3.202 ± 0.7523 g, p=0.0563; 37.82 ± 19.05 g vs. 31.43 ± 20.99 g, untransformed) (Table 2-10, Figure 2-13). The control was not found to be significantly different from two consecutive years of 100% stem harvest (p=0.1101), but the p-value dropped when pairwise comparisons were conducted on harvest treatments separately from trampling treatments (3.497 ± 0.5575 g vs. 3.214 ± 0.7572 g, p=0.0778; 37.82 ± 19.05 g vs. 31.84 ± 21.02 g, untransformed). When harvest treatments were analyzed separately, harvest of 100% stems for one year followed by one year of rest was found to yield greater AG biomass than harvest at the same level without one year rest, but the difference was not statistically significant at the 0.05 level (3.366 ± 0.6082 g vs. 3.087 ± 0.8199 g, p=0.0876; 34.38 ± 21.07 g vs. 28.98 ± 20.67 g, untransformed).

When Dunnett's test was used to compare treatments to the control (i.e., no harvest or trampling), AG biomass in the following treatments was significantly less than the control (3.497 ± 0.5575; 37.82 ± 19.05 g, untransformed) at the 0.05 level: 25% stem harvest for two consecutive years (3.202 ± 0.7523, p=0.010; 31.43 ± 20.99 g untransformed); 100% harvest for one year (second year only/with no rest) (3.087 ± 0.8199, p<0.001; 28.98 ± 20.67 g, untransformed); and two consecutive years of 100% stem harvest (3.214 ± 0.7572, p=0.015; 31.84 ± 21.02 g, untransformed) (Table 2-6). These results were very similar to those when harvest treatments were analyzed separately. When the trampling treatments were analyzed with the harvest treatments or separately, none was found to differ significantly from the control (though when the two most robust blocks (BN1 and BN2) were removed from the analysis, the p-value for two consecutive years of trampling was p=0.115).

In order to account for the possible contribution of dead AG biomass to these results, dead AG biomass was subtracted from total AG biomass and analysis was conducted on live AG biomass at two sites within the wildlife refuge. Treatment effect was not significant (p=0.209, with no site-treatment interaction term in the model and with block treated as a random factor). Site-treatment interaction was not found to be significant for live AG biomass plots at the two sites within the wildlife refuge (p=0.7912), so it was not included in the model used for the ANOVA.

Stem Caliber

Natural log stem caliber did not differ significantly among treatments (p=0.248), even when harvest and trampling treatments were analyzed separately (p=0.213 and p=0.350, respectively) (Table 2-11, Figure 2-11). No post-hoc tests were conducted on this attribute.

Belowground Biomass

Natural log of BG biomass did not differ significantly among treatments in the north- and south-shore blocks within the wildlife refuge (p=0.9082 when interaction term was included in model, and 0.8932 when no interaction term was in the model and block was treated as a random factor). The interaction of site and treatment was found not to be significant (0.9470).

Dead Stems

Natural log of density of dead stems did not differ among treatments in the north- and south-shore blocks within the wildlife refuge (p=0.1603 when site-treatment interaction was included in the model, and p=0.153 when no interaction term was included in the model and when block was treated as a random factor). Difference among treatments remained insignificant when harvest and trampling treatments were analyzed separately (p=0.140 and p=0.309, respectively). No post-hoc tests were conducted on this attribute.

Dead Aboveground Biomass

Natural log of dead AG biomass did not differ among treatments in the north- and south-shore blocks within the wildlife refuge (p=0.233), when no interaction term was included in the model and when block was treated as a random factor. The site-treatment interaction was found not to be significant (p=0.4817). When harvest and trampling treatments were analyzed separately, treatment effect remained not significant (p=0.142 and p=0.667, respectively). No post-hoc tests were conducted on this attribute.

Summary of Quantified Effects of Treatments

Maximum stem height was negatively affected by several treatments. For *S. pungens* stands of all stem heights tested (i.e., taller than 70 cm), a decrease in stem height of 6.4-6.7

cm was caused by harvest of 100% stems for one year without rest or for two consecutive years. For stands with maximum height below 130 cm, a significant decrease of 6.3-8.2 cm was caused by harvest of 100% or 25% stems for two consecutive years or by harvest of 100% stems for one year without rest. Maximum stem height may not be affected by 100% stem harvest when stands are over 130 cm tall. Trampling for two consecutive years may decrease maximum stem height by 4.5 cm.

Aboveground (AG) biomass was negatively affected by some harvest treatments. A significant decrease of 5.98-8.84 g was caused by harvest of 100% or 25% stems for two consecutive years or by harvest of 100% stems for one year without rest.

Stem density was also negatively affected by some harvest treatments. A significant decrease of 13.4-17.9 stems/0.0625 m^2 was caused by harvest of 100% stems for two consecutive years or for one year without rest.

Since AG biomass is a function of a combination of stem height and stem density, it is not surprising that most of these responses to treatments are similar.

To summarize by treatment, two consecutive years of 100% stem harvest negatively affected stem height (except possibly for stands over 130 cm), stem density and AG biomass. The same is true of one year of 100% stem harvest without a year of rest. Two consecutive years of 25% stem harvest negatively affected maximum stem height (for stands shorter than 130 cm) and AG biomass. Trampling for two consecutive years may affect maximum stem height in stands of all heights over 70 cm (i.e., the subset of stands tested).

DISCUSSION

Guidelines for Sustainable Sweetgrass Harvest

In general, harvest of 100% stems had more negative effects than 25% harvest. Harvesting treatments of two consecutive years or no rest after one year of harvesting had negative effects on some sweetgrass attributes. Two consecutive years of harvest created a cumulative effect that would be expected to continue with additional years of consecutive harvest without rest. In practice, patches that are shorter than others are less likely to be harvested in a given year, since taller stems are preferred by weavers, so there may be a self-regulating dimension to harvesting practices.

These results suggest the following guidelines for sustainable harvest: a) harvest stems of 130 cm or taller because they may not be affected by harvest; b) allow at least one year of rest after every harvest so that the plant can recover to some degree (generally, the more years of rest, the more recovery can be expected); c) harvest at the 25% level or lower to have less impact than 100% harvest and so that the plant requires less recovery time; and d) avoid trampling in the same location during two consecutive years. These guidelines could form the basis for subsequent controlled studies focused on sustainable harvest.

Comparison to Other Studies

A few comparisons can be made to previous studies. Turner and Peacock's (2005:145) emphasis on the regenerative ability of perennials is partially supported. sSome treatments, especially 100% harvest without rest, do have a negative effect on plant attributes and have the potential to deplete populations over time. The guidelines presented above increase the chances of successful regeneration of sweetgrass following harvest. I did not find that harvesting increased stem height as might be expected from a decrease in intrspecific competition, though this possibility could be the focus of a future study (Turner and Peacock 2005:143). Anderson and Rowney's (1999:231) finding that 50% harvest of blue dicks bulbs was more sustainable than 100% harvest is consistent with my findings that 25% harvest of sweetgrass was more sustainable than 100% harvest. However, direct comparison is difficult because of the functional differences in plant structures: bulbs contain meristems (i.e., regeneration sites), whereas sweetgrass stems do not. In a small pilot study, Cullis-Suzuki et al. (2015:31, 33) stated that 30% harvest appeared to be sustainable for the rhizomatous eelgrass *Zostera marina* and was analogous to traditional collection practices using a twist stick. This harvest intensity is comparable to the 25% harvest treatment used in the sweetgrass study.

The morphology of *S. pungens* (i.e., erect stems and rhizomes with underground meristems) appears to make it resilient in response, if not resistant, to at least one year of trampling, as predicted by Cole (1995:215). Eckrich and Homquist's (2000) work with trampling effects on the seagrass *Thalassia testudinum* suggests that *S. pungens* has the advantage of tougher tissues that help it resist impact. However, the tallest, most robust sweetgrass stems grow in softer substrate rather than firmer sandy substrate and may therefore be more vulnerable to trampling impact. It is possible that the ability of taller stems to recover from impact may compensate for greater vulnerability to effects of trampling in soft substrates. Some gatherers recognize that taller sweetgrass stems typically grow in softer, muddier substrate at lower elevations (Shale-Berstrom, personal communication), but harvested patches are often seen at higher elevations (personal observation). Taller stems can be found in some higher-elevation locations where freshwater inputs reduce salinity levels (personal observation), but gatherers that do not venture to those places or lower, muddier elevations would probably find stems that overall are shorter than elsewhere.

Indigenous People, Public Lands and Grays Harbor National Wildlife Refuge

The co-location of a gathering ground visited by generations of Native Americans and a wildlife refuge managed by U. S. Fish and Wildlife Service requires that we consider the history of indigenous people and public lands. Indigenous people not only occupied and used the resources of North America long before European contact, but they also manipulated their environments to increase resource quantities and qualities (see Deur and Turner's (2005) *Keeping It Living: Traditions of Plant Use and Cultivation on the Northwest Coast of North America* and Anderson's (2005) *Tending the Wilderness: Native American Knowledge and the Management of California's Natural Resources*). Following contact, Native Americans were removed from their homelands and home waters, sometimes to newly designated areas of residence to make way for Euro-American re-settlers and sometimes to the territory of a neighboring group where a reservation was established for "consolidated" tribes. Many groups were left without a land base or without ecosystems that provided important materials, leaving them dependent on public lands (Bishop and Hansen 1978:23, Marino 1990:171, Anderson 1996:417, Shebitz and Crandell 2012:169). What is less well known is that many indigenous people were removed from areas the United States government established as national parks and other public lands given various kinds of "natural" area or wilderness status, including Mount

Rainier and Olympic National Parks in Washington State (Dowie 2009:1, 11). As these people were excluded, so were their cultural practices that had been integral parts of and in some cases helped form the landscape (Anderson 1996:415). But these many decades after displacement, lack of access to culturally important plants or management of public lands without cultural goals is the source of considerable concern to groups such as the Skokomish, who emphasize the importance of cedar on the Olympic Peninsula (Pavel et al. 1993:64) By contrast, managers of some public lands, such as national forests, work with Native American tribes to provide access to culturally important plants such as beargrass and huckleberries, which are valued by the Confederated Tribes of Siletz Indians (Robert Kentta, personal communication; personal observation). Public lands often contain the few remaining populations of valued plant species, and private property ownership prevents access to many others (Anderson 1996:418-9). There is a growing call from workers such as Anderson (2005:356; 1996:418) to increase the exercise of gathering rights and traditional cultural practices on public lands.

These considerations apply to GHNWR, which is a relatively new refuge established in 1996. To reduce and monitor harvesting pressure on sweetgrass, USFWS prohibited non-native weavers from harvesting in GHNWR and developed a permit system for Native American weavers that specifies quantity, use and timing of harvest. Some gatherers adhere to the system and others do not on the grounds of historic practice (Seto, personal communication; Ryan 2000:110). References to sweetgrass collection in Grays Harbor have been in the historic record since the late 1800's, but the environmental history of the Hoquiam River and Bowerman Basin reveals that the sweetgrass stands have developed at the current location within the last century. It is likely that sweetgrass migrated along the north shore of the inner bay and that the weavers followed. Harvesting has been part of this stretch of shoreline since at least the 1950's (james and Martino 1986:74). As with many cultural practices, knowledge of gathering grounds must be "historicized" in recognition of the significant disruptions to culture, including changes to the landscape, since the time of contact with European Americans (Butler 2006:107).

The rise in interest in Native American basketry since the cultural renewal of the 1970's and the establishment of the *American Indian Basketry Magazine* in 1979, the formation of the Northwest Native American Basketweavers Association in 1996, and the efforts to improve biocultural health through basketry groups suggest the potential for more harvesting pressure on the region's primary sweetgrass gathering grounds (Bowechop, et al. 2012; Crawford-O'Brien 2013:219). Plant stem height has decreased in some areas, but that appears to be a result of sediment trapping and changes in freshwater inputs, rather than harvest pressure. (Sedimentation is a natural estuarine process, though timber practices that increase sedimentation in the bay may accelerate that process.) Sweetgrass stands are continuing to expand westward, and adaptive shifts in gathering grounds may occur as they have for decades on this shoreline. Renewed interest in the use of canoes may facilitate awareness of new stands and also promote selective harvest of the most desirable patches. Ultimately, it is hoped that all stakeholders benefit from an understanding of sweetgrass gathering grounds in the context of naturally dynamic systems and in terms of function rather than strictly in the terms of geographical location. Full details of the shift in gathering grounds, the historic use of canoes in harvesting, and the proposal to understand gathering grounds functionally rather than strictly geographically are provided in Chapter 3, "Following the Sweetgrass: Environmental

History and Cultural Geography of *Schoenoplectus pungens* in Bowerman Basin and Surrounding Watersheds."

Ecological Restoration

As is the case with any intertidal species, restoration of *S. pungens* requires some planning and a lot of luck. The dynamism of the environment and the difficulty of predicting combinations of key variables in specific locations complicate the undertaking. In the late 1990's, *S. pungens* was added to a USFWS Coastal America site on the Duwamish River, where *Carex lyngbyei* and other estuarine marsh species had been successfully established after goose exclosures were used to reduce grazing pressure (Crandell 2001). The salinity, elevation, substrate and goose protection allowed the plantings to get a good start, but the low salinity levels during the early part of the growing season and low energy of the shoreline seemed to ultimately favor other species. *S. pungens* was outcompeted to the point at which very few stems could be found several years after planting (personal observation).

In light of the concerns about the condition of gathering grounds in Bowerman Basin and in the context of re-establishing culturally important ecosystems, sweetgrass has been included in the estuarine restoration efforts of several tribes in the Pacific Northwest. The results have been mixed. The Skokomish Indian Tribe has been interested in restoring sweetgrass since the 1990's, and dike removal and re-introduction of tidal influence began in 2007 (Lamberson 1996; Grimley 2007; Dublancia, personal communication). Recent reports of the watershed-wide project, including intertidal marsh restoration, do not mention successful sweetgrass re-establishment (Skokomish Watershed Action Team

2016). The dams and water diversion associated with hydropower in the upper watershed likely continue to affect the timing and volume of freshwater inputs, as well as coarse sediment, so sweetgrass stands may be unlikely to re-establish to historic levels (Fischer 2014, Gleason 2016). The Cowlitz acquired land in the Lower Columbia River, where they also planned to breach a river dike on the south side of the Columbia and include sweetgrass if conditions were suitable (Stout, personal communication). The low energy of the site suggests that *S. pungens* may not be able to outcompete other species.

The best news on the restoration front has come from the Nisqually Indian Tribe. They planted sweetgrass on the east side of the Nisqually River in 2013, several years after two plantings of the sweetgrass were included in a large restoration project in the adjacent Billy Frank Jr. Nisqually National Wildlife Refuge. Harwell (2015) studied these three locations. At least one of the stands on the refuge has not survived; the other two stands appear to be doing well. Regular monitoring of the stands, which was to have begun in 2015, may help determine if they can withstand harvesting, which was the original reason for including them (Harwell 2015). However, Anderson (2005:344) suggests limiting harvesting plants in restored areas in order to avoid overharvesting and encourages gathering in neighboring areas instead. Given the destruction of estuaries in Puget Sound, it is not clear that remaining stands, if they exist, could withstand harvesting better than the plantings. If harvesting is tried, the guidelines for sustainable practices provided in this study may prove helpful.

Future Research and Collaboration

This study is one of very few controlled experiments conducted on the harvesting of culturally important native species. The data analysis provided the basis for guidelines for sustainable harvest of established stands, and I recommend that those guidelines become starting points for future research. It would be important to test more than two years of consecutive harvest and to establish the number of years of rest required for full recovery after both 100% and 25% harvest. The 25% harvest was implemented on the scale of stems within a plot. Because efficiency is sometimes a priority as the tide rolls in, testing the scales to which 25% applies would be helpful. In other words, could 25% of stems in a patch be sustainable if removed by handfuls rather than a single stem at a time. Similarly, could a square meter of stems (the typical size of a harvest patch) be removed and remain sustainable if at least 3 square meters are left untouched? Among the qualities valued in sweetgrass stems, and other plants, is suppleness (James and Martino 1986:73, 76; B. L. Ryan, personal communication). I have observed that stems are more supple in areas shaded by bordering willows or by forested promontories or bluffs that cast afternoon shadows on the marsh. Determining the role played by shaded conditions in the growth of the most desired material would be useful (see also Nordquist and Nordquist 1983:13 for beargrass (*Xerophyllum tenax*) and Turner et al. 1983:79 for slough sedge (*Carex obnupta*)).

Beyond the quantitative aspects of the research, it will be critical to work with tribes and First Nations that depend on the existence of and access to sweetgrass for spiritual reasons as well as cultural expression. As the poet Gail Tremblay (Onondaga/Mic Mac) (1990:39) wrote in a poem about gathering sweetgrass in Shoalwater Bay (Willapa Bay), “We bent and stood in rhythmic/motion thinking of our ancestors plucking the ancestors of this grass/. . . /the fiber used to keep the ancient art alive.” When I started this work, it was my hope that I would be able to work with Native American gatherers to conduct the experiment. I did base the harvesting treatments on techniques I had seen used in the field or had been learned from Native American weavers (especially Loa and Teresa Ryan). Over the years, I have been able to spend time with half a dozen experienced Native American weavers and gatherers and talk specifically about sweetgrass, but I did not work with them in the field. The labor-intensive work across 24 blocks and four sites in Grays Harbor required 45 ten-hour-plus people-days in the field during the peak of the growing season. Logistical challenges included a) limited work windows scheduled strictly around tides, b) travel to sites by hand-powered boat or by hiking over very uneven terrain, and c) physically demanding tasks. Before implementing this experiment, I did not have time to develop relationships with local tribes and therefore relied on fellow graduate students and interested friends to complete the field work. The next steps in this research are best undertaken in collaboration with Native Americans and First Nations, as called for by Menzies (Ts'msyen (Tsimshian)) (2006:240): "I can recognize the clear value in actually listening to the people closest to the resource, the people who live there, work there, and know the resource in an intimate and profound fashion." He provided guidelines for collaborative research in an article entitled "Putting Words into Action: Negotiating Collaborative Research in Gitxaala" (Menzies 2005). Cullis-Suzuki et al. (2015) provide a good example of this approach in a pilot study on eelgrass that used techniques developed from interviews with Kwakwaka'wakw elders, was directed by the clan chief, and was conducted with other members of their village in collaboration with non-Indigenous scientists.

Sweetgrass studies that address not only the technical questions but also logistical considerations and labor needs will take a lot of planning. It is my hope that this study will make some of that planning easier. As Menzies (2005:27) stated, “[W]hether one is an Indigenous scholar or not we all share a responsibility to conduct respectful research that demonstrates not just the form, but the actual content of respect and honour.”

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Table 2-1. Treatments applied to plots in randomized block design.

Number	Treatment	Representing
0	C3	Control (no treatment, sampled in year 3)
1	H1-1-25	Harvested 1 year, year 1, 25% of stems
2	H1-2-25	Harvested 1 year, year 2, 25% of stems
3	H2-25	Harvested 2 years, 25% of stems
4	H1-1-100	Harvested 1 year, year 1, 25% of stems
5	H1-2-100	Harvested 1 year, year 2, 25% of stems
6	H2-100	Harvested 2 years, 100% of stems
7	T1-1	Trampled 1 year, year 1
8	T1-2	Trampled 1 year, year 2
9	T2	Trampled 2 years

Table 2-2. Randomized block design across sites: 1 = north shore of Bowerman Basin; 2 = south shore of Bowerman Basin; 3 = Chenois Creek; 4 = Grass Creek. Treatment abbreviations as in Table 2-1.

Site	**Block**	**Treatment**									
		H1-1-25	**H1-2-25**	**H2-25**	**H1-1-100**	**H1-2-100**	**H2-100**	**T1-1**	**T1-2**	**T2**	**C3**
1	1	X	X	X	X	X	X	X	X	X	X
	2	X	X	X	X	X	X	X	X	X	X
	3	X	X	X	X	X	X	X	X	X	X
	4	X	X	X	X	X	X	X	X	X	X
	5	X	X	X	X	X	X	X	X	X	X
	6	X	X	X	X	X	X	X	X	X	X
	7	X	X	X	X	X	X	X	X	X	X
	8	X	X	X	X	X	X	X	X	X	X
2	9	X	X	X	X	X	X	X	X	X	X
	10	X	X	X	X	X	X	X	X	X	X
	11	X	X	X	X	X	X	X	X	X	X
	12	X	X	X	X	X	X	X	X	X	X
	13	X	X	X	X	X	X	X	X	X	X
3	14	X	X	X	X	X	X	X	X	X	X
	15	X	X	X	X	X	X	X	X	X	X
	16	X	X	X	X	X	X	X	X	X	X
	17	X	X	X	X	X	X	X	X	X	X
	18	X	X	X	X	X	X	X	X	X	X
	19	X	X	X	X	X	X	X	X	X	X
	20	X	X	X	X	X	X	X	X	X	X
	21	X	X	X	X	X	X	X	X	X	X
4	22	X	X	X	X	X	X	X	X	X	X
	23	X	X	X	X	X	X	X	X	X	X
	24	X	X	X	X	X	X	X	X	X	X

Table 2-3. Means and standard deviations of a) untransformed and b) natural log-transformed data for maximum stem height, aboveground biomass, stem density, and stem caliber for all treatments. All measurements were made in a 25 cm-by-25 cm (0.0625 m^2) quadrat within a 1 m^2 plot. Maximum stem height and stem caliber were measured for 5 tallest stems in a quadrat. * denotes treatments significantly different from control, using Dunnett's test on natural log-transformed data, with α=0.05. + denotes Dunnett's test results with $p<0.10$. (See Table 2-6 for Dunnett's test p-values and data subsets.) δ denotes difference from control. Treatment abbreviations as in Table 2-1.

a. Untransformed data

	Ln Maximum Stem Height (cm)		Ln Maximum Stem Height (cm) (w/o BN1, BN2)		Ln Aboveground Biomass (g)		Ln Stem Density		Ln Stem Caliber (mm)	
Treatment	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
C3	4.624	0.1858	4.582	0.1230	3.497	0.5575	4.374	0.5939	1.703	0.1788
H1-1-25	4.595	0.1960	4.551	0.1320	3.442	0.5834	4.335	0.7061	1.718	0.2216
H1-2-25	4.595	0.1907	4.550	0.1221	3.351	0.4704	4.290	0.5323	1.684	0.1952
H2-25	+4.565	0.2114	*4.513	0.1242	*3.202	0.7523	4.317	0.6679	1.709	0.2031
H1-1-100	4.596	0.2023	4.549	0.1286	3.366	0.6082	4.195	0.7365	1.745	0.1976
H1-2-100	*4.548	0.2250	*4.494	0.1327	*3.087	0.8199	*3.976	0.9448	1.694	0.2147
H2-100	*4.557	0.2056	*4.512	0.1451	*3.214	0.7572	*4.046	0.9175	1.760	0.2361
T1-1	4.611	0.1782	4.567	0.1012	3.580	0.4983	4.434	0.5754	1.713	0.2159
T1-2	4.630	0.1485	4.601	0.1149	3.481	0.5603	4.307	0.6220	1.763	0.1575
T2	+4.581	0.1855	4.539	0.1255	3.412	0.5888	4.255	0.7023	1.740	0.2118

b. Natural log-transformed data

	Ln Maximum Stem Height (cm)		Ln Maximum Stem Height (cm) (w/o BN1, BN2)		Ln Aboveground Biomass (g)		Ln Stem Density		Ln Stem Caliber (mm)	
Treatment	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
C3	4.624	0.1858	4.582	0.1230	3.497	0.5575	4.374	0.5939	1.703	0.1788
H1-1-25	4.595	0.1960	4.551	0.1320	3.442	0.5834	4.335	0.7061	1.718	0.2216
H1-2-25	4.595	0.1907	4.550	0.1221	3.351	0.4704	4.290	0.5323	1.684	0.1952
H2-25	+4.565	0.2114	*4.513	0.1242	*3.202	0.7523	4.317	0.6679	1.709	0.2031
H1-1-100	4.596	0.2023	4.549	0.1286	3.366	0.6082	4.195	0.7365	1.745	0.1976
H1-2-100	*4.548	0.2250	*4.494	0.1327	*3.087	0.8199	*3.976	0.9448	1.694	0.2147
H2-100	*4.557	0.2056	*4.512	0.1451	*3.214	0.7572	*4.046	0.9175	1.760	0.2361
T1-1	4.611	0.1782	4.567	0.1012	3.580	0.4983	4.434	0.5754	1.713	0.2159
T1-2	4.630	0.1485	4.601	0.1149	3.481	0.5603	4.307	0.6220	1.763	0.1575
T2	+4.581	0.1855	4.539	0.1255	3.412	0.5888	4.255	0.7023	1.740	0.2118

Table 2-4. Natural log maximum stem height AVOVA tables for no interaction model with blocks treated as random effects. Outlier blocks BN1 and BN2 removed from second, fourth and sixth analyses. In last four analyses, harvest and trampling treatments analyzed separately but compared to same control. * denotes significance at the 0.05 level.

Ln(maximum stem height)	**df**	**SS**	**MS**	**F**	**Pr(>F)**
Error: block					
Site	3	1.314	0.4379	1.53	0.237
Residuals	20	5.723	0.2862		
Error: within					
Treatment	9	0.1646	0.018290	2.35	0.0152*
Residuals	207	1.6109	0.007782		
W/o BN1 & BN2					
Error: block					
Site	3	0.5808	0.19361	2.759	0.0723
Residuals	18	1.2633	0.07019		
Error: within					
Treatment	9	0.2165	0.024052	3.114	0.00162*
Residuals	189	1.4596	0.007723		
Harvest Only					
Error: block					
Site	3	0.841	0.2805	1.202	0.335
Residuals	20	4.667	0.2333		
Error: within					
Treatment	6	0.1047	0.017446	2.166	0.0499*
Residuals	138	1.1113	0.008053		
Harvest Only w/o BN1 & BN2					
Error: block					
Site	3	0.478	0.159	3.006	0.057
Residuals	18	0.954	0.053		
Error: within					
Treatment	6	0.123	0.020	2.461	0.028*
Residuals	126	1.048	0.008		
Trampling Only					
Error: block					
Site	3	0.5765	0.19215	2.202	0.119
Residuals	20	1.7456	0.08728		
Error: within					
Treatment	3	0.0351	0.011708	1.616	0.194
Residuals	69	0.4999	0.007245		

Trampling Only w/o BN1 & BN2					
Error: block					
Site	3	0.207	0.069	2.531	0.090
Residuals	18	0.491	0.027		
Error: within					
Treatment	3	0.045	0.015	2.137	0.104
Residuals	63	0.443	0.007		

Table 2-5a. Natural log maximum stem height results for Tukey HSD test using no interaction model. Table includes pairwise comparisons that are significantly different ($\alpha = 0.05$; denoted with *) or have p-values <0.10. See Figure 2-8 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. Outlier blocks BN1 & BN2 were removed for some analyses. Abbreviations as in Table 2-1.

Ln(maximum stem height)				
Treatment comparison	**Difference**	**Lower limit**	**Upper limit**	**P-value**
All Treatments				
C > H1-2-100	-7.605604e-02	-0.1575094918	0.005397411	0.0898006
T1-2 > H1-2-100	8.184947e-02	0.0003960201	0.163302923	0.0477930*
Without BN1 & BN2				
C>H1-2-100	0.0882488779	0.003408350	0.17308941	0.0342*
T1-2>H1-2-100	0.1076960212	0.022855493	0.19253655	0.0028*
T1-2>H2-100	0.0891724622	0.004331934	0.17401299	0.0307*
T1-2>H2-25	0.0878949555	0.003054428	0.17273548	0.0356*
Harvest Only				
C > H1-2-100	7.605604e-02	-0.001460428	0.15357251	0.0582288
Without BN1 & BN2				
C > H1-2-100	0.0882488779	0.00583838	0.17065938	0.0274248*
Trampling Only				
None				
Without BN1 & BN2				
T1-2 > T2	0.06199552	-0.00472229	0.12871332	0.0777352

Table 2-5b. For natural log maximum stem height, summary of pairwise comparisons significant at alpha = 0.05 (denoted with *) and with p-values <0.10 based on Tukey HSD test using no interaction model. See Figure 2-8 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. Outlier blocks BN1 & BN2 were removed for some analyses. Tmt=treatments, H=harvest, T=trampling. Individual treatment abbreviations as in Table 2-1.

Ln(maximum stem height)						
Treatment comparison	**All Tmt**	**All Tmt w/o BN1 & BN2**	**H Tmt Only**	**H Tmt Only w/o BN1 & BN2**	**T Tmt Only**	**T Tmt Only w/o BN1 & BN2**
C > H1-2-100	0.0898	0.0342*	0.0582	0.0274*		
T1-2 > H1-2-100	0.0478*	0.0028*				
T1-2>H2-100	0.1211	0.0307*				
T1-2>H2-25	0.2479	0.0356*				
T1-2 > T2	0.6397	0.3687			>0.1	0.0777

Table 2-6. For natural log-transformed maximum stem height, aboveground biomass, and stem density, summary of Dunnett's test results for treatments that are significantly less than the control (α=0.05; denoted with *) or for which $p<0.10$. See Figures 2-11 in which these results are incorporated into boxplots of all treatments. Tests were conducted for all treatments, as well as harvest and trampling treatments separately using the same control. Two blocks (BN1 and BN2) had maximum stem heights that were exceptionally tall and stem calibers that were exceptionally large, and these outliers were removed in some analyses (see Figure 2-8). Treatment was not significantly different for stem caliber results. T2 (trampling for 2 years) was included because results are potentially biologically meaningful when trampling is analyzed separately. Treatment abbreviations as in Table 2-1.

Plant Attribute & Dataset	**Treatments < Control**			
	H2-25	**H1-2-100**	**H2-100**	**T2**
Maximum stem height	0.064	0.012*	0.030*	0.210
w/o BN1 & BN2	0.035*	0.004*	0.031*	0.250
Harvest only	0.054*	0.010*	0.025*	
Trampling only				0.096
Aboveground biomass	0.010*	0.000*	0.015*	
w/o BN1 & BN2	0.010*	0.000*	0.015*	
Harvest only	0.015*	0.015*	0.014*	
Stem Density		0.000*	0.005*	
w/o BN1 & BN2		0.001*	0.007*	
Harvest only		0.000*	0.005*	

Table 2-7. Natural log stem density AVOVA tables for no interaction model with blocks treated as random effects. In second and third analyses, harvest and trampling treatments were analyzed separately but compared to same control. * denotes significant difference, with α=0.05. See Figure 2-11 for boxplot of all treatments.

Ln(stem density)

	df	**SS**	**MS**	**F**	**Pr(>F)**
Error: block					
Site	3	64.96	21.65	16.52	1.22e-05*
Residuals	20	26.21	1.31		
Error: within					
Treatment	9	4.45	0.4945	4.027	9.1e-05*
Residuals	207	25.42	0.1228		
Harvest Only					
Error: block					
Site	3	52.24	17.412	18.45	5.6e-06*
Residuals	20	18.88	0.944		
Error: within					
Treatment	6	3.40	0.5666	4.439	0.0003888*
Residuals	138	17.61	0.1276		
Harvest Only w/o BN1 & BN2					
Error: block					
Site	3	53.958	17.986	20.818	0.000*
Residuals	18	15.551	0.864		
Error: within					
Treatment	6	3.170	0.528	4.243	0.001*
Residuals	126	15.688	0.125		
Trampling Only					
Error: block					
Site	3	19.041	6.347	13.9	3.99e-05
Residuals	20	9.135	0.457		
Error: within					
Treatment	3	0.443	0.1477	1.308	0.279
Residuals	69	7.793	0.1129		

Table 2-8a. Natural log stem density results for Tukey HSD test using no interaction model. Table includes pairwise comparisons that are significantly different ($\alpha = 0.05$; denoted with *) or have p-values <0.10. See Figure 2-12 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. No pairwise comparisons were significant for trampling-only comparisons. Treatment abbreviations as in Table 2-1

Treatment comparison	Difference	Lower limit	Upper limit	P-value
All Treatments				
H1-2-25 > H1-2-100	0.31404171	-0.009504921	0.6375883	0.0652704
T1-2 > H1-2-100	0.33044649	0.006899854	0.6539931	0.0409301*
H2-25 > H1-2-100	0.34117556	0.017628925	0.6647222	0.0296594*
H1-1-25 > H1-2-100	0.35911065	0.035564021	0.6826573	0.0168268*
C > H1-2-100	0.39801099	0.074464358	0.7215576	0.0043915*
T1-1 > H1-2-100	0.45829586	0.134749226	0.7818425	0.0004158*
C > H2-100	0.32772997	0.004183334	0.6512766	0.0443153*
T1-1 > H2-100	0.38801484	0.064468202	0.7115615	0.0062906*
Harvest Only				
H1-2-25 > H1-2-100	0.31404171	0.005439052	0.6226444	0.0432243*
H2-25 > H1-2-100	0.34117556	0.032572897	0.6497782	0.0200254*
H1-1-25 > H1-2-100	0.35911065	0.050507994	0.6677133	0.0116010*
C > H1-2-100	0.39801099	0.089408331	0.7066137	0.0032319*
H1-1-25 > H2-100	0.28882963	-0.019773030	0.5974323	0.0827536
C > H2-100	0.32772997	0.019127307	0.6363326	0.0295781*

Table 2-8b. For natural log stem density, summary of pairwise comparisons significant at alpha = 0.05 (denoted with *) and with p-values <0.10 based on Tukey HSD test using no interaction model. See Figure 2-12 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. No pairwise comparisons were significant for trampling only comparisons. Treatment abbreviations as in Table 2-1.

Treatment Pairwise Comparison	All Treatments	Harvest Only
H1-2-25 > H1-2-100	0.0652704	0.0432243*
T1-2 > H1-2-100	0.0409301*	
H2-25 > H1-2-100	0.0296594*	0.0200254*
H1-1-25 > H1-2-100	0.0168268*	0.0116010*
C > H1-2-100	0.0043915*	0.0032319*
H1-1-25 > H2-100	0.1253833	0.0827536
T1-1 > H1-2-100	0.0004158*	
C > H2-100	0.0443153*	0.0295781*
T1-1 > H2-100	0.0062906*	

Table 2-9. Natural log aboveground biomass AVOVA tables for no interaction model with blocks treated as random effects. In second and third analyses, harvest and trampling treatments were analyzed separately but compared to same control. * denotes significant difference, with α=0.05.

Ln(aboveground biomass)					
	df	**SS**	**MS**	**F**	**Pr(>F)**
Error: block					
Site	3	56.93	18.978	35.48	3.36e-08*
Residuals	20	10.70	0.535		
Error: within					
Treatment	9	5.081	0.5646	4.97	4.66e-06*
Residuals	207	23.514	0.1136		

Harvest Only					
Error: block					
Site	3	43.16	14.388	27.48	2.7e-07*
Residuals	20	10.47	0.524		
Error: within					
Treatment	6	3.062	0.5103	4.241	0.000597*
Residuals	138	16.607	0.1203		

Trampling Only					
Error: block					
Site	3	19.208	6.403	59.7	3.69e-10*
Residuals	20	2.145	0.107		
Error: within					
Treatment	3	0.342	0.1139	1.173	0.326
Residuals	69	6.700	0.0971		

Table 2-10a. Natural log aboveground biomass results for Tukey HSD test using no interaction model. Table includes pairwise comparisons that are significantly different (α = 0.05; denoted with *) or have p-values <0.10. See Figure 2-8 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. No pairwise comparisons were significant for trampling only. Treatment abbreviations as in Table 2-1.

Ln(aboveground biomass)				
Treatment comparison	**Difference**	**Lower limit**	**Upper limit**	**P-value**
All Treatments				
T2 > H1-2-100	0.32474331	0.01354187	0.6359448	0.0330422*
H1-1-25 > H1-2-100	0.35421339	0.04301195	0.6654148	0.0124349*
T1-2 > H1-2-100	0.39402281	0.08282137	0.7052243	0.0028557*
C > H1-2-100	0.41003284	0.09883140	0.7212343	0.0015110*
T1-1 > H1-2-100	0.49245785	0.18125640	0.8036593	0.0000398*
C > H2-25	0.29527334	-0.01592811	0.6064748	0.0789868
T1-1 > H2-25	0.37769834	0.06649690	0.6888998	0.0053253*
T1-1 > H2-100	0.36530866	0.05410722	0.6765101	0.0083912*
Harvest Only				
H1-1-100 > H1-2-100	0.27816161	-0.021490236	0.5778135	0.0876396
H1-1-25 > H1-2-100	0.35421339	0.054561543	0.6538652	0.0097009*
C > H1-2-100	0.41003284	0.110380991	0.7096847	0.0013709*
C > H2-25	0.29527334	-0.004378511	0.5949252	0.0562883
C > H2-100	0.28288365	-0.016768197	0.5825355	0.0778147

Table 2-10b. For natural log aboveground biomass, summary of pairwise comparisons significant at alpha = 0.05 (denoted with *) and with p-values <0.10 based on Tukey HSD test using no interaction model. See Figure 2-8 for plot of all treatments analyzed together. Harvest and trampling treatments were also analyzed separately but were compared to same control. No pairwise comparisons were significant for trampling only comparisons. Treatment abbreviations as in Table 2-1.

Ln(aboveground biomass)		
Treatment Pairwise Comparison	**All Treatments**	**Harvest Only**
H1-1-100 > H1-2-100	0.1242716	0.0876396
T2 > H1-2-100	0.0330422*	
H1-1-25 > H1-2-100	0.0124349*	0.0097009*
T1-2 > H1-2-100	0.0028557*	
C > H1-2-100	0.0015110*	0.0013709*
T1-1 > H1-2-100	0.0000398*	
C > H2-25	0.0789868	0.0562883
T1-1 > H2-25	0.0053253*	
C > H2-100	0.1101094	0.0778147
T1-1 > H2-100	0.0083912*	

Table 2-11. Natural log stem caliber AVOVA tables for no interaction model with blocks treated as random effects. Outliers in BN1 and BN2 were removed in the second, fourth and sixth analyses. In the last four analyses, harvest and trampling treatments were analyzed separately but compared to same control. No post-hoc tests were conducted. * denotes significant difference, with $\alpha=0.05$.

Ln(stem caliber)					
	df	**SS**	**MS**	**F**	**Pr(>F)**
Error: block					
Site	3	1.170	0.3900	1.414	0.268
Residuals	20	5.517	0.2758		
Error: within					
Treatment	9	0.1627	0.01808	1.282	0.248
Residuals	207	2.9175	0.01409		
W/o BN1 & BN2					
Error: block					
Site	3	1.159	0.3865	5.615	0.00675*
Residuals	18	1.239	0.0688		
Error: within					
Treatment	9	0.178	0.01978	1.427	0.179
Residuals	189	2.619	0.01386		
Harvest Only					
Error: block					
Site	3	0.639	0.2130	0.94	0.44
Residuals	20	4.533	0.2267		
Error: within					
Treatment	6	0.1082	0.01803	1.416	0.213
Residuals	138	1.7575	0.01273		
Harvest Only w/o BN1 & BN2					
Error: block					
Site	3	0.7541	0.25136	5.295	0.00856*
Residuals	18	0.8544	0.04747		
Error: within					
Treatment	6	0.0875	0.01459	1.134	0.346
Residuals	126	1.6206	0.01286		

Trampling Only					
Error: block					
Site	3	0.5757	0.1919	2.181	0.122
Residuals	20	1.7601	0.0880		
Error: within					
Treatment	3	0.0519	0.01731	1.112	0.35
Residuals	69	1.0742	0.01557		

Trampling Only w/o BN1 & BN2					
Error: block					
Site	3	0.555	0.185	5.411	0.008*
Residuals	18	0.616	0.034		
Error: within					
Treatment	3	0.062	0.021	1.318	0.277
Residuals	63	0.994	0.016		

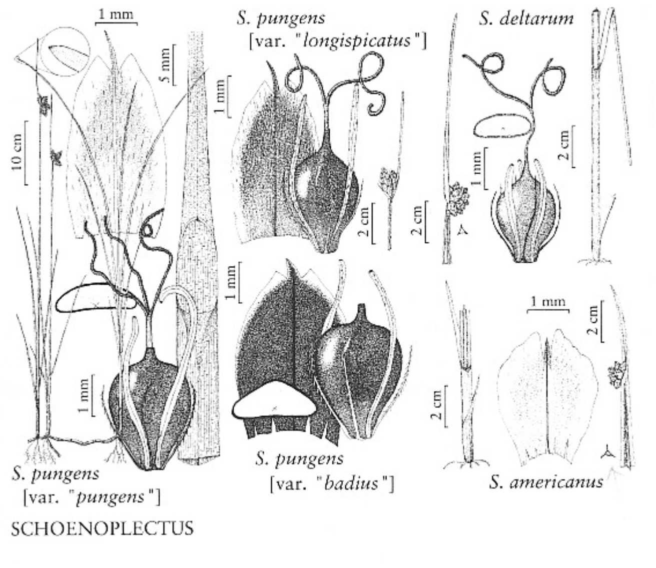


Figure 2-1. Top drawings of *Schoenoplectus pungens* (formerly called Scirpus americanus in the Pacific Northwest) by Jeanne R. Janish are from *Vascular Plants of the Pacific Northwest* (Hitchcock et al. 1969:372). Bottom drawings by Susan A. Reznicek are from the *Schoenoplectus* section in *Flora of North America: North of Mexico* (Smith (2002:51). *S. pungens var. badius* is native to the coastal marshes of the Pacific Northwest.

Figure 2-2. Baskets made with sweetgrass. Top row: Loa Ryan (Ts'msyen). (Photos: Mitchell Almaguer-Bay) Middle row: Quinault. Bottom row: Louisa Pulsifer (Skokomish). (Photos in bottom two rows: Burke Museum of Natural History and Culture; object numbers 2.5E1149 and 2.5E1618, respectively)

Figure 2-3. Trails and harvested patches of sweetgrass are visible on north shore of Bowerman Basin near railroad trestle (eastern) access point, August 2000. (Photo: Caren Crandell)

Figure 2-4. Pulling stems in treated plots of harvesting experiment. The traditional method is to pull rather than cut the stems. For 25% harvest treatments, stems were pulled one at a time, whereas handfuls could be pulled in the 100% harvest treatments. (Photo: Caren Crandell)

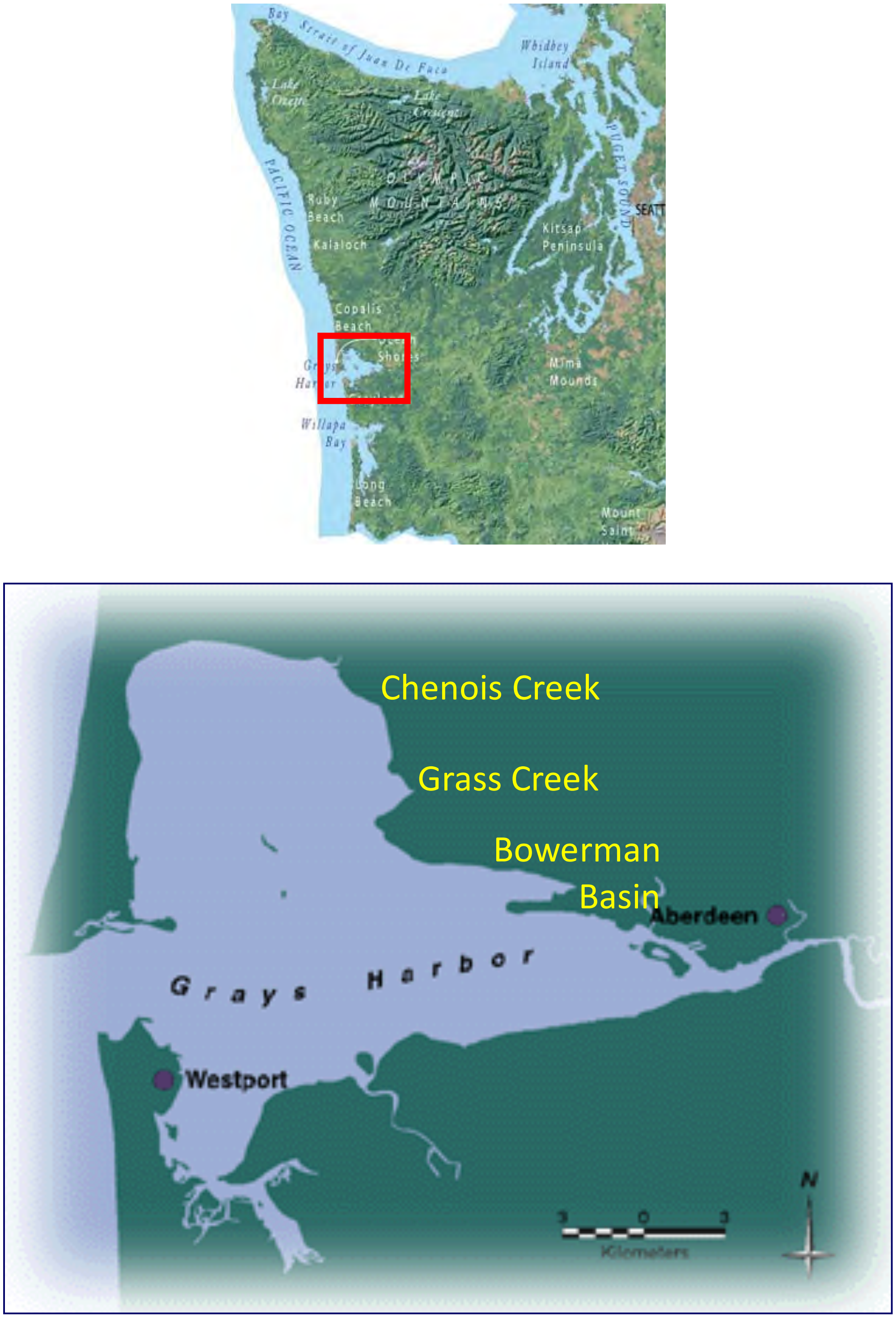
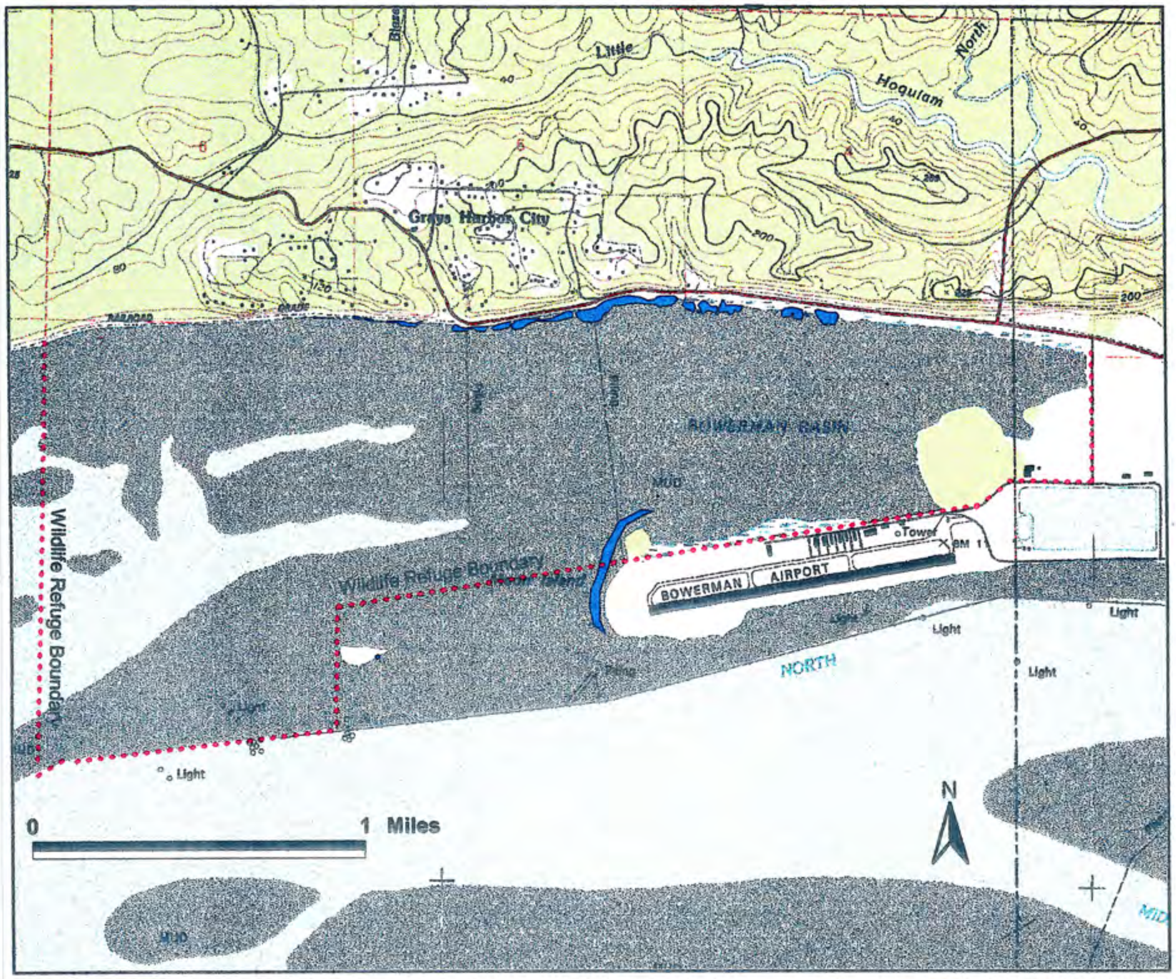


Figure 2-5. Regional maps. Top: Western Washington with Grays Harbor highlighted (source: www.bentler.us). Bottom: Grays Harbor with coastal study sites marked (source: Pacific Northwest Coastal Ecosystem Regional Study). North and south shores of Bowerman Basin were treated as two different sites due to different site histories.



*Schoenoplectus pungens (=Scirpus americanus) in blue shaded areas.
Mapped Aug/Sep 1998. Shoreline is approximate mean high water.

Hoquiam, WA USGS 7.5 Quad
1957 (rev. 1994)

Figure 2-6. *Schoenoplectus pungens* (blue polygons) in Bowerman Basin in Grays Harbor Wildlife Refuge, Hoquiam, Washington. Mapping was conducted in August and September 1998. (Crandell 1999)

Chenois Creek

Grass Creek

Figure 2-7a. Oblique aerial photos of sites, from north to south, of harvesting experiments. Extensive stands of *Schoenoplectus pungens* exist at each of these sites. Top: Bowerman Basin shoreline looking north. Bottom: Bowerman Basin south shoreline looking east. (Photos: Washington State Department of Ecology, Shoreline Photo Viewer, dated 11 August 2016)

Figure 2-7b. Oblique aerial photos of sites, from north to south, of harvesting experiments. Extensive stands of *Schoenoplectus pungens* exist at each of these sites. Top: North shore of Bowerman Basin looking north. Bottom: South shore of Bowerman Basin looking east. (Photos: Washington State Department of Ecology, Shoreline Photo Viewer, dated 11 August 2016)

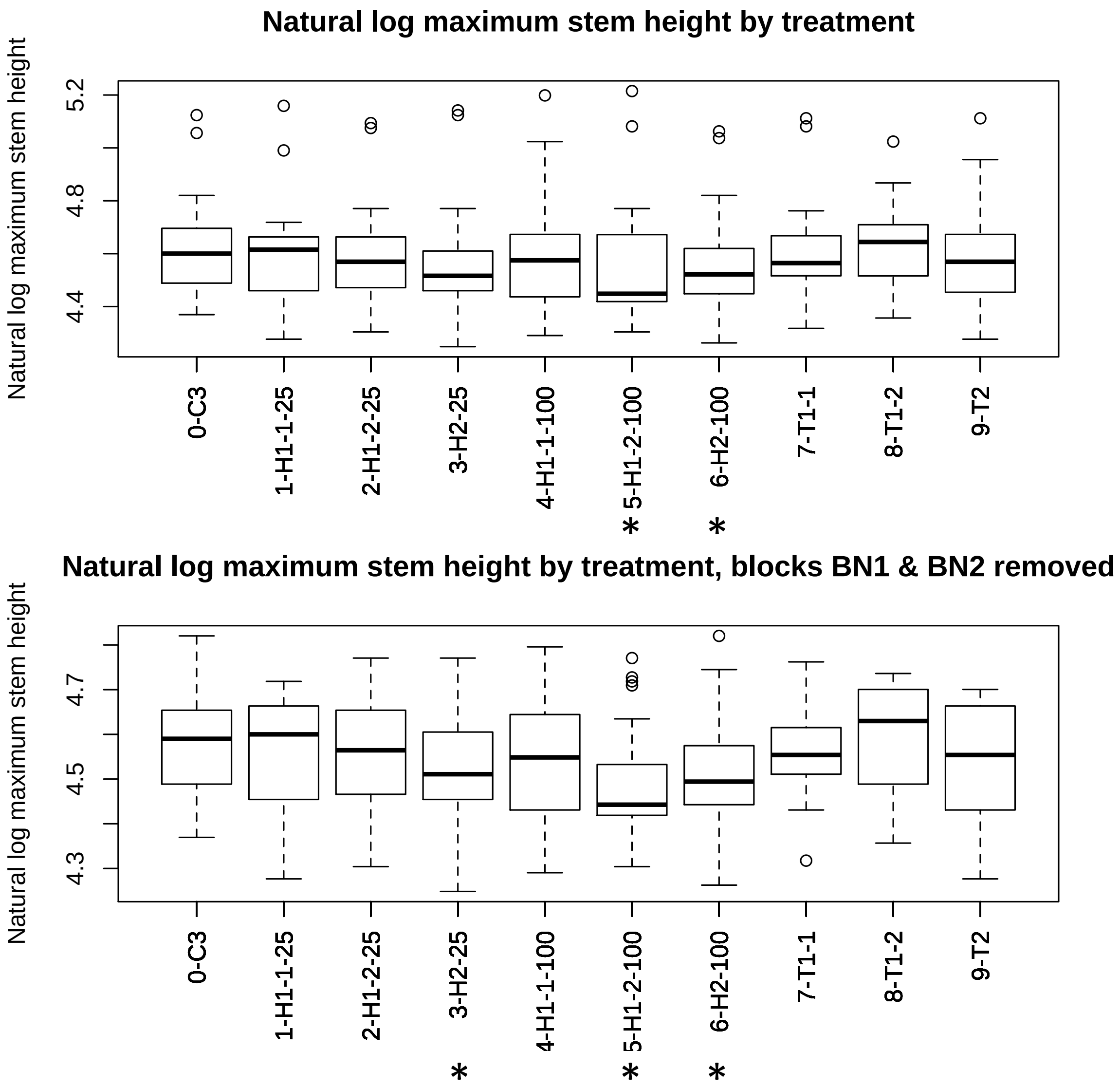


Figure 2-8. Comparison of boxplots of natural log maximum stem height by treatment, with and without with tall stems in blocks BN1 and BN2 removed from dataset. Outliers in the top boxplot are tall stems in blocks BN1 and BN2, which are removed in bottom boxplot. * denotes treatment significantly different from the control, using Dunnett's test with α=0.05. Without outliers BN1 and BN2, treatment H2-25 is also significantly different from the control at the 0.05 level. See Table 2-4 for ANOVA results and Table 2-6 for Dunnett's test results. Treatment abbreviations as in Table 2-1.

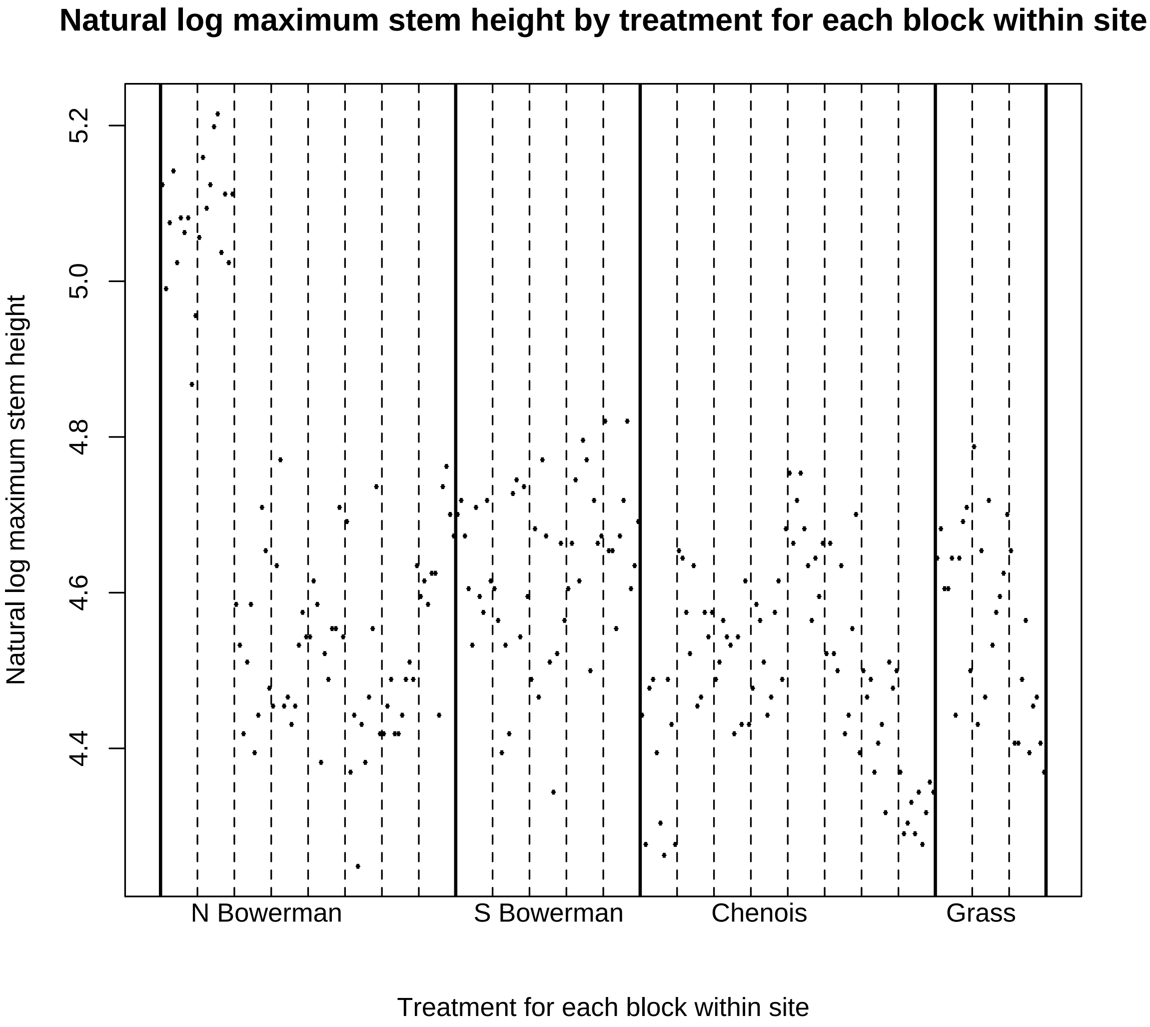


Figure 2-9. Natural log maximum stem height plotted by treatment for each block within site. Order of treatments is as in Table 2-1 (0-C3 to 9-T2, left to right within each block). Note tallest stems in the two blocks (BN1 and BN2) at North Shore Bowerman Basin, which were removed in some subsequent analyses.

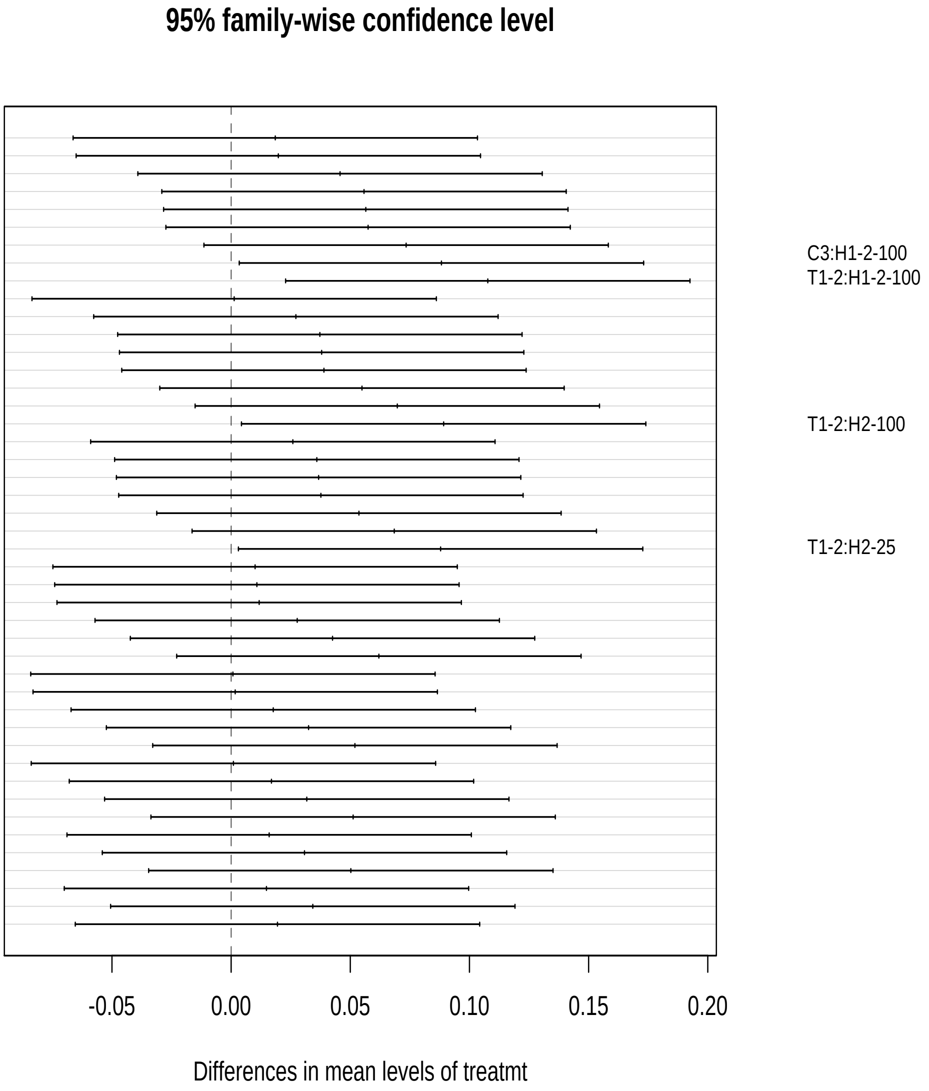


Figure 2-10. Tukey HSD test plot of 95% family-wise confidence levels (CL) for treatment comparisons of natural log of maximum stem height, without outlier blocks BN1 and BN2. Those CLs that do not include zero indicate that those treatments are significantly different (α=0.05). Only significantly different pairs of treatments are labeled. See Table 2-5 for CLs and p-values. Abbreviations as in Table 2-1.

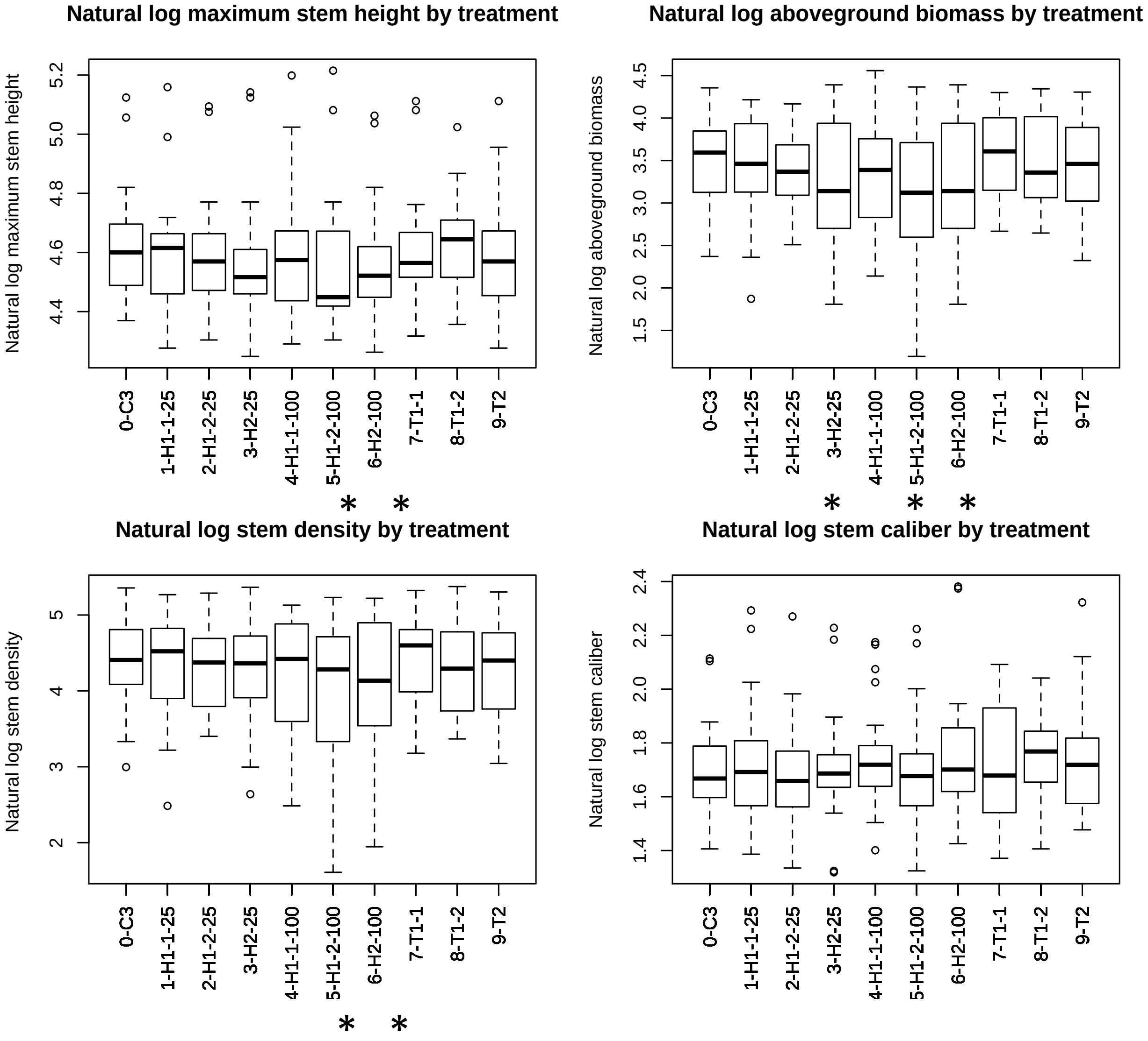


Figure 2-11. Boxplots of natural log of maximum stem height, aboveground biomass, stem density, and stem caliber by treatment. * denotes treatments significantly different from the control, using Dunnett's test with α=0.05 (see Table 2-6). Treatment abbreviations as in Table 2-1.

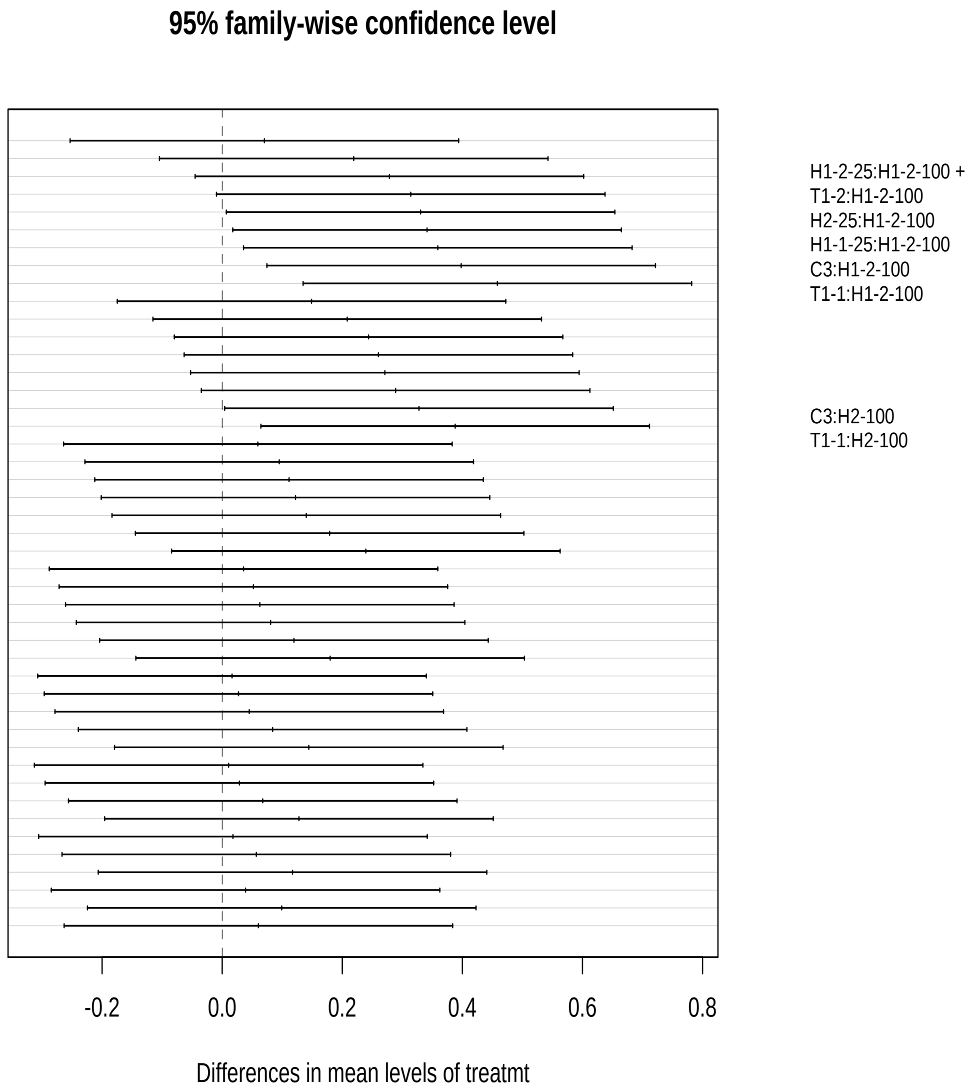


Figure 2-12. Tukey HSD test plot showing 95% family-wise confidence levels (CL) for treatment comparisons of natural log of stem density. Those CLs that do not include zero indicate that those treatments are significantly different (α=0.05). Only significantly different pairs of treatments are labeled. See Table 2-8 for CLs and p-values. Abbreviations as in Table 2-1. + denotes p-value greater than 0.05 but less than 0.10.

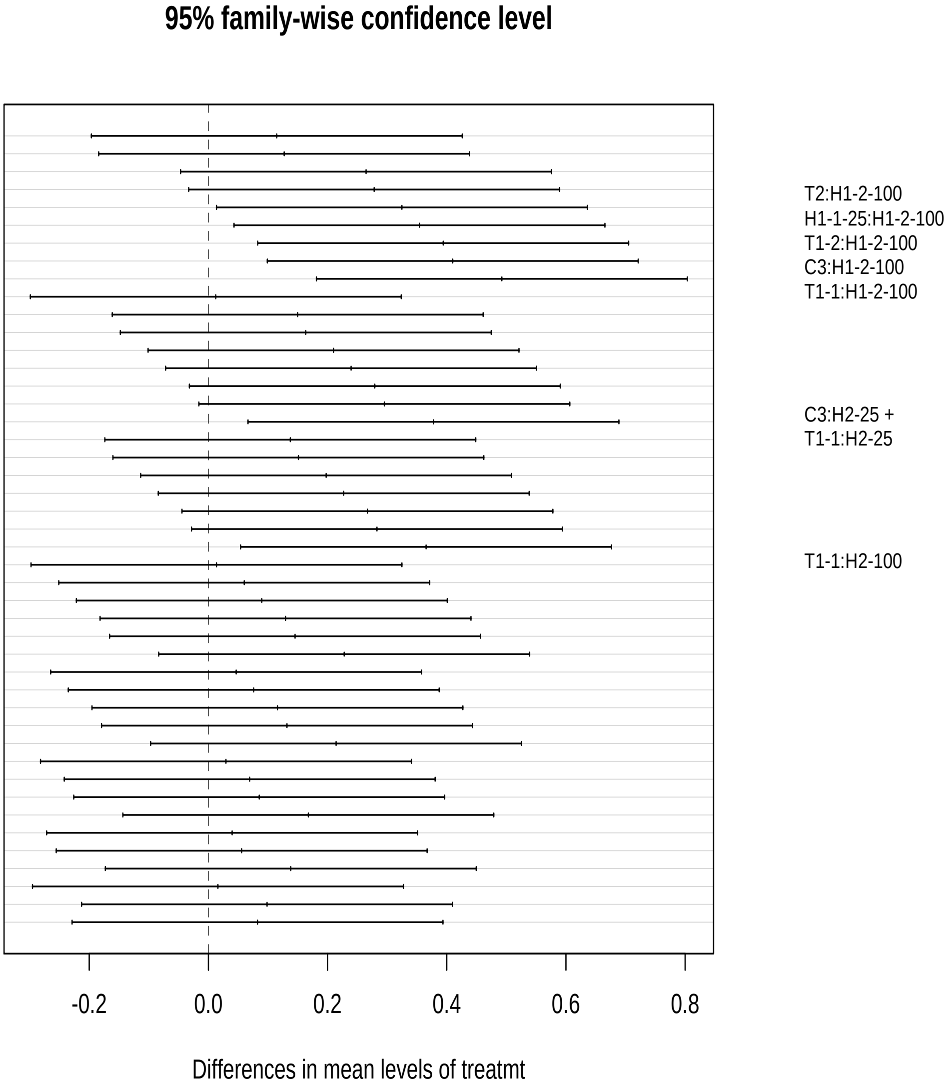


Figure 2-13. Tukey HSD test plot of 95% family-wise confidence levels (CL) for treatment comparisons of natural log of aboveground biomass. Those CLs that do not include zero indicate that those treatments are significantly different (α=0.05). Only significantly different pairs of treatments are labeled. See Table 2-10 for CLs and p-values. Abbreviations as in Table 2-1. + denotes p-value greater than 0.05 but less than 0.10.

CHAPTER 3. Following the Sweetgrass: Environmental History and Cultural Geography of *Schoenoplectus pungens* in Bowerman Basin (Grays Harbor) and Surrounding Watersheds in Western Washington

ABSTRACT

Is sweetgrass (*Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith) on the decline? A native species in the estuarine marshes of the Pacific Northwest, this species is ecologically important; and as a fiber used in the basketry of local Native American tribes, the plant is culturally important. When the Grays Harbor National Wildlife Refuge was established in 1996, some local Native American weavers told the U. S. Fish and Wildlife Service staff that the species was diminishing in quality. For most weavers, that means that stems are shorter, though length-width ratio and suppleness are also important. According to some gatherers, the area occupied by the stands may also be be shrinking. To assess the plant's status, I began monitoring the extensive stands on the north and south shores of Bowerman Basin in 1999. For a number of years, the data did not show a trend in stem height, stem density, stem caliber or aboveground biomass; so the ecological answer appeared to be that the species was not in decline.

The more time I spent with weavers, the more determined I became that the "yes" and "no" answers to the question must somehow both be true. I continued to monitor the stands for ten years and later combined that field work with an examination of the environmental history of the Hoquiam River delta and the cultural geography of weavers and their sweetgrass gathering grounds. The monitoring data showed that from 1999 to 2008, the trends were mixed, but there was support for the concern that the stand was on

the decline in terms of stem height and the extent of the stands in some locations in Bowerman Basin that was frequented by gatherers.

However, a mystery remained because the environmental history of Bowerman Basin included a great deal of shoreline modification that created the basin itself, and no evidence of marshes or sweetgrass until the middle of the last century. After examining historical charts, surveys, photos, anthropological reports, and studies by the Corps of Engineers, I suggest that sweetgrass would have been present in the Hoquiam River delta and Rennie Island, and that it migrated along the shoreline as the tide flats were filled in with the establishment and expansion of the City of Hoquiam. I also suggest that weavers would have followed the sweetgrass, which would have been relatively easy by canoe. Later reliance on car transportation has limited access to sweetgrass stands, and most gatherers now visit stands next to highways. This shift represents an adaptive response to changes in environmental conditions, which Indigenous people have engaged in for millennia.

Because weavers from a number of regional tribes now gather sweetgrass in Bowerman Basin, I also considered changes in surrounding watersheds that have led weavers to shift their gathering grounds from their home waters to that basin. In the North Bay of Grays Harbor, extensive stands of sweetgrass are found on the shoreline between the Humptulips River and Chenois Creek. Shifts in harvesting grounds from this area to Bowerman Basin would have occurred as Native Americans were displaced and came to rely on wagon and then car transportation from the Quinault and other reservations to the bay. The disruptive factors at work in the Skokomish River delta include agriculture and hydropower. Dikes were built to keep out the influence of tides and river floods. Later, two dams and a diversion in the upper watershed altered the timing and volume of freshwater inputs to the estuary that favor species such as sweeetgrass. Under the strain of these modifications, remaining stands of sweetgrass became too sparse to provide a sustainable source of the fiber, and Skokomish weavers also turned to the Bowerman Basin stands. So on a regional level, sweetgrass has been on the decline for decades.

These shifts in gathering grounds are examples of adaptive responses to anthropogenic change that affected the environment and disrupted cultural practices. Adaptive responses have always been an aspect of Indigenous ecological knowledge (IEK) and argue for understanding gathering grounds in terms of function rather than strictly geographic location. Meaning tied to significant places, including gathering grounds, has been explained as a product of space, experience, and time (Thornton 2008:10). Given the rapid change resulting from human activities in the last 150 years in Western Washington, the time associated with a given place may be on the order of decades rather than centuries. Adopting a functional approach to documenting meaningful places requires regularly updating use-and-occupancy maps. These documents support protection of the environmental rights of Native Americans, which are cultural rights and, ultimately, human rights.

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A. Introduction: Is Sweetgrass on the Decline?

Is sweetgrass on the decline? The answer to this question is important because, as a native species in the estuarine marshes of the Pacific Northwest (PNW), *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith), has ecological significance (Figure 3-1); and as a fiber used in the basketry of local Native American tribes, the plant has cultural importance (Figures 3-2 and 3-3). The question was initially posed by the U.S. Fish and Wildlife Service (USFWS) staff at the Nisqually National Wildlife Refuge Complex in response to concern expressed by Native American weavers and out of concern for the habitat USFWS manages in Grays Harbor Wildlife Refuge (Seto, personal communication).

"Decline" is an ambiguous term, and I rarely heard anyone define it precisely. I have developed a composite, inclusive description based on a lot of listening over the years. Gathering grounds have diminished because of habitat loss in numerous Pacific Northwest estuaries and because access that relies on automobile transportation to public lands rather than the traditional canoe (Shebitz and Crandell 2012:167; see also later sections below). Sweetgrass quality is usually characterized by stem length, height-to-width ratio, suppleness, and lack of spotting by decomposers (Shebitz and Crandell 2012:166). In the primary gathering ground of Bowerman Basin in Grays Harbor, the concern is that stems are shortening, the stand is shrinking, and stems are spotting (B. L. Ryan, personal communication; S. T. Ryan, personal communication; Harradine, personal communication). So many tribes and weavers now rely on this one shoreline for sweetgrass that the stands in Bowerman Basin may be experiencing more harvesting pressure than they can withstand without negative effect. Overharvesting is a concern because the stands in the Skokomish River estuary were said to have been overharvested, though hydropower and agriculture may have been the primary causes for the diminished delta marsh, as I will discuss in the last portion of this paper (Nordquist and Nordquist 1983:13).

So, is sweetgrass on the decline? For a few years, there were two answers: that sweetgrass was indeed on the decline, according to several Native American tribes and weavers in the Pacific Northwest; and on the other hand, that it was expanding, according to recent historical evidence augmented by my field work. I started this work as a plant ecologist with a genuine interest but no training in Native American culture; but as time passed, I became convinced that my scientific perspective was limited and limiting and that both answers must somehow be true. And so I set out to find the one story that integrated all the evidence.

In this paper, I focus on *S. pungens* (formerly known as *Scirpus americanus* in the PNW) in the context of the environmental history of Grays Harbor, Washington, and the cultural geography of the weavers that use it in basketry. I follow the sweetgrass and the gatherers along the shore and in four watersheds as both respond to human impacts on the landscape (Figure 3-4). The environmental history, in combination with more recent ecological field work, and the cultural experience shared by Native American weavers represent “different paths to knowledge” that “are rooted in the same reality” (Mazzocchi 2006:466). With this integrated story, I attempt to create a common understanding of environmental and cultural change, strengthen the case for access to this cultural resource, suggest that gathering grounds be defined functionally rather than strictly geographically, consider adaptive change in the context of cultural resilience, and show how “different paths to knowledge” can converge.

B. Literature Review

1. The lived landscape: place-making among Native Americans

Place is inherently a human creation borne of experience, a result of living in the landscape. Places are defined spaces that develop meaning to people through interaction with the landscape, and that meaning borne of experience lasts over time (Thornton 2008:10). Place-making, or consciousness of place, is part of our "deep collective human heritage," wrote Thornton (2008: 107). He focused on the Tlingit people and their homeland in what is also called Southeastern Alaska, but the concept is applicable to all indigenous peoples. Thornton (2008) defined place as a combination of elements: space, experience, and time. Space is the concrete, physical location; experience is the lived interaction with the landscape; and time addresses the longstanding practice associated with the space and the repeated nature or awareness of the experience within lifetimes and across generations. Relationships with the land and water are built through the cultural structures associated with material production, social organization, language, and ritual processes (Thornton 2008:35). Through these structures, places in the lived landscape thus acquire meaning.

Because of the role of time in place-making, the temptation is to assume these spaces with meaning endure unchanged. But both the spaces themselves and their meanings can change. And so we must allow for or accommodate such changes as we try to understand the occupancy and land use of Native Americans. Through developing the history of sweetgrass gathering grounds in Grays Harbor, Washington, I acknowledge the centrality of place to Native American life but also demonstrate how ecological and cultural change must be incorporated into our understanding of the lived landscape.

Among indigenous people of North America, documentation of place-names has become an important means of preserving knowledge and supporting land claims and the right to access resources. Tobias (2000, 2009) in *Chief Kerry's Moose* and *Living Proof* provided guidance for mapping land-use and occupancy of First Nations. These maps draw on oral histories and may be called "the geography of oral tradition" (Tobias 2000:xi). They incorporate knowledge of resources in the landscape that is variously known as traditional knowledge (TK), traditional ecological knowledge (TEK), local knowledge (LK), or Indigenous knowledge (IK). These terms are often used interchangeably to reflect the basis for Indigenous practices, despite different assumptions or connotations associated with the terms (Butler 2006:108). As explained later, Indigenous Ecological Knowledge (IEK) is used in this paper (Butler 2006:121). Among the places noted on a map might be gathering grounds for culturally important plants, hunting grounds or the site of a significant hunt, clam-digging sand flats, and prime fishing spots. Any map by its nature features geographically specific locations, but Tobias (2000:xii) recommends periodic updating of the maps because "[c]ulture is not static or fixed in stone—patterns of occupancy and use change over time."

2. *Culture is dynamic, and patterns of use change*

Ecological conditions, cultural functions, and even personal or spiritual significance may change with the passage of time. Examples of ecological change that required cultural adaptation include changes in the routes of salmon-bearing stream channels as they enter estuaries (Langdon 2006:33); decrease in salmon population/abundance during the lower temperatures of the Little Ice Age of the mid- to late 1800's (Langdon 2006:21, 43); and westward migration of the Fraser River delta, and hence salmon fishing grounds (Stevenson 1998:222). Examples of cultural practices that responded to environmental change include extension of wood-stake fishing weirs/traps over 1,000 years in response to isostatic uplift and mudflat-expanding sedimentation along the coast of SE Alaska (Moss and Erlandson 1998:190); and relocation of a Tlingit village in SE Alaska following a major iceberg release (Langdon 2006:21).

A more complex example of the interplay between cultural practices and ecological change on the Northwest Coast began about 5,000 years ago. Sea levels, coastlines, and associated aquatic ecosystems stabilized; and in response, salmon populations increased in adjacent streams (Arnold 2008:21; Fladmark et al 1990:229). Archaeological records of middens (4,000 to 6,000 years old) show that salmon then became more important in the diets of the inhabitants of the region (Arnold 2008:21; Davis 1990:199). Wood-stake weirs carbon-dated to 3,000 years B.P. indicate cultural practices centered on salmon fishing – and necessarily, processing and storage of large quantities of animal protein (Moss et al. 1990:152-3). In other words, as the abundance of salmon grew, the culture not only added them to their diet but adapted by developing efficient means of catching them (Arnold 2008:21). Over time, people "began to build their societies around availability of salmon" (Arnold 2008:21), and the anadromous fish came to "virtually dictat[e] the economic cycle" (De Laguna 1990:210). Extended families established year-round villages on salmon streams or moved to fishing camps during the summer months when the concentrated runs arrived (De Laguna 1990:210). Later, villages were also established along rivers, where multiple species of salmon could be found and provide a reliable source of food year after year (Arnold 2008:21). One Tlingit historian explained the centrality of salmon to the location of villages: “That’s why they lived there; [salmon] made it a village” (Arnold 2008:21).

To illustrate the dynamism of both landscapes and the cultures that inhabited them, Nicholas (1998:39) presented examples from the archaeological record of changes in hunter-gatherer use of North American wetlands. In regions such as the Lower Klamath of California and the Great Basin, land use changes might have corresponded to environmental changes that affected wetland productivity and species composition. Coot hunting 7,000 years ago gave way, centuries later, to grebe hunting, which ultimately gave way to scaup hunting (Nicholas 1998:41). (Shifts in food preferences may also be due to overexploitation of one species.) Wetlands might initially have been used seasonally for waterbird hunting, but – in an otherwise arid landscape – these and additional resources might have become increasingly important for subsistence. After several thousand years, seasonal residences and might then have become permanent villages, with lifeways becoming more sedentary (Nicholas 1998:40). Another reason for the advent of more sedentary lifeways might have been an increase in productivity of, and therefore reliance on, wetlands in the Great Basin when climate became wetter about 1,500 years ago (Nicholas 1998:39; Lyle et al. 2012). So, the environment and ecosystems clearly change, and the knowledge possessed by cultures that rely on them changes along with them.

3. Putting indigenous knowledge and experience in historical context

Butler (2006) notes that knowledge – whether TEK, IK or LK – is based on experience, and we have to recognize and account for the fact that change of a different kind was also visited on Indigenous peoples of North America. During the last two centuries, enormous cultural disruption characterized the Native American experience in the Pacific Northwest. Colonialism brought dislocation from homelands, policies prohibiting collection of resources, exclusion from areas newly designated as private property, and mandatory education of children in boarding schools, all of which had an impact on knowledge and its transmission. Knowledge held today would have responded to and emerged out of these years of multiple modes of disruption. Butler's (2006:126) concern is that this impact be taken into account and that TEK be properly "historicized." She fears that, in the literature and in practice, the failure to understand TEK in the context of recent history creates problems, especially when that knowledge is turned to for solutions to environmental challenges – e.g., to mitigate ecological damage or ameliorate environmental conditions created by European American colonizers. In other words, knowledge that has been modified in response to cultural disruption and ecological degradation may not be the most useful tool for reversing or repairing ecological damage. Equally concerning, Indigenous people are set up for failure.

This disconnect also argues for de-emphasis of "traditional" in "traditional ecological knowledge" and for use of the terms "local knowledge" or "Indigenous knowledge" (IK) or "Indigenous ecological knowledge" (IEK) instead. As explained further in the next section, Tobias (2009:33) expressed concern about "traditionalism" connoting a resistance to change, which would be a view held for the benefit of the colonizing power. For these and other reasons expanded upon in the next section, IK and IEK are used in this paper.

So, bringing together the work of Tobias and Butler, we need, on one hand, to map land use and occupancy while recognizing that these patterns may shift due to environmental or ecological changes; and on the other hand, we need to be mindful that, whatever places associated with IEK can be mapped now, the knowledge on which the map is based has grown out of experience affected by contact with colonizing forces. Ultimately, we have to view culture as dynamic and expect and account for change caused by several factors. In this paper, I draw on the essential recognition of the response of IEK to various aspects and realities of cultural disruption in order to understand shifts in the sweetgrass gathering grounds of Grays Harbor.

4. Indigenous knowledge and adaptive change

In interactions between cultures, power affects the perception or interpretation of change. Tobias (2009:33) expressed concern about the use of the word “traditional” to describe Indigenous use of homelands because it supports stereotypes. He wrote that governments have been interacting with First Nations from the perspective of “traditionalism,” or “the upholding or maintenance of tradition, especially so as to resist change” (Tobias 2009:33). This resistance to change on the part of governing powers may be used – deliberately or unintentionally – to limit the rights of Indigenous people. Commenting on the poem “Changing Is Not Vanishing” by Wassaja Carlos Montezuma (Yavapai), Parker (2011:36) observed that “static models of authenticity [are projected] onto colonized peoples as a way of denying the colonized people’s ongoing life and resistance to colonialist authority.” Butler (2006:124) wrote that Indigenous knowledge is “trapped in history” and is contrasted to Western knowledge that is “modern and dynamic,” a dichotomy that marginalizes the former in service to the latter. Tobias (2009:33) argued that cultures are not static, and “[a]daptive change is inherent in every tradition.” For this reason, I use the terms Indigenous ecological knowledge (IEK) or Indigenous knowledge

(IK), which do not fix practices at a moment in time and do allow for the change that has characterized the connection between culture and ecology for thousands of years. IEK and IK are therefore conceptually consistent with the goals of this paper.

In this study, I look at the environmental history of the Grays Harbor estuary and put the sweetgrass gathering grounds into a historical context that includes the impacts of contact with European American settlement and the cultural resilience of Native American people of the region. Ecological changes have occurred in response to human actions, and IEK has tracked both kinds of changes to maintain access to a valued weaving material. Understanding these changes and the cultural response is particularly important in Southwest Washington, where treaty negotiations between the U.S. government and tribes collapsed, and access to resources does not have the legal footing it would in other parts of Washington, where treaties do apply. Adaptive change will be shown to have both a long legacy and ongoing relevance.

5. From canoes to cars: effects of changes in transportation

Among the changes in practices that are relevant to sweetgrass is the change in modes of transportation. Indigenous peoples living along miles of coasts and rivers in the PNW historically relied on water for mobility. In fact, waterways determined where villages were located (Capoeman 1991:45, 53). Boats are obviously a practical way to get around in a watery environment, but in many ways water-travel was more practical than travel on land that was covered with dense forest vegetation, as was typical of much of the Northwest Coast (Capoeman 1991:23, 45; Turner 1998:20).

Women used canoes to reach gathering grounds for weaving materials, many of which grew in wetlands, and, in flooded conditions, gathered plant materials while seated or standing in them (Figures 3-5, 3-6 and 3-7). Lela Morganroth (Quileute) plied the waters of Lake Ozette with her grandmother to collect cattails and other materials and, on overnight trips, slept in the canoe (Halliday and Chehak 1996:125). In an Edward S. Curtis photo, two women are shown gathering cattails from a canoe in Puget Sound (Curtis 1913: plate facing page 112; Nordquist and Nordquist 1983:21; Figure 3-6). In a series of photos taken by Curtis of the Cowichan in 1910 and 1912, a woman is shown harvesting tule (*Schoenoplectus tabernaemontani*) and balancing a bundle of stems on the bow of her canoe in preparation for the trip home (Curtis 1913: plates facing pages 82-88, plate no. 315; Figure 3-5). Louisa Pulsifer (Klallam/Skokomish; b. 1882, d. 1979) paddled her dugout canoe to different marine and river locations on Hood Canal to gather fiber for weaving (Burke Museum of Natural History and Culture 2001). Emily Miller (Twana) was photographed (sometime between the 1952 and 1976) poling her canoe, piled high with cattails, along a shallow river channel (Nordquist and Nordquist 1983:12, Figure 3-7). She and Louisa Pulsifer worked with anthropologists to record their knowledge of weaving materials and gathering practices (Nordquist and Nordquist 1983:13):

> Access to the cattail stands was usually from water by boat. At low tide the boat was beached and the gatherers would cut the stalks close to the mud surface. . . . The harvested cattails were piled in one end of the boat, or dugout canoe in earlier times, and taken to the summer camp. The boat was poled upstream when the tide was in and the river current was least strong.

John Thomas (Ditidaht, formerly Nitinaht) retraced his family's gathering rounds via canoe; sweetgrass, cattail and tule were collected in the alluvial flats of the Cheewhat River on the west coast of Vancouver Island (Turner et al. 1983:2, 12). For some, canoes gave way to other types of boats. Shoalwater Bay Tribal Elder Anita Shipman Couture remembered Agnes James, an older neighbor on the reservation who “made baskets, [and] picked grass out in the bay in a rowboat” in 1942 (Altruda Anderson 1998:90).

These examples in the PNW make clear that sweetgrass and other marsh species were approached from the water side rather than the land side of the stands. Traditional travel by canoe would have made all tidal resources, and therefore sweetgrass stands, accessible. In Grays Harbor, canoe traffic dropped around 1900, in part as Native Americans were dislocated and in part as roads were built for travel by wagon and then automobile (Capoeman 1991:101, 106). This shift meant that access to tidal marsh plants would be from the land side rather than water. Access from land has a number of ramifications.

Logistically, road routes determine where gatherers can get close to the marsh. In Grays Harbor, S. R. 109 only brings drivers next to sweetgrass stands at Bowerman Basin. Here, there are two pull-out points along the highway, both of which are filled areas that are remnants of the shoreside ends of overwater structures (i.e., on the east, a railroad trestle used to aid construction of airport and, to the west, Grays Harbor City wharf). These two areas provide fixed access points to the marsh, which results in much more limited exposure to sweetgrass stands than would be achieved by canoe. Canoe travel would allow a gatherer to scan a shoreline for the most desirable portions of a stand - perhaps the tallest or most dense stems. In Bowerman Basin, weavers gather within a relatively small radius of the access points and may not be aware of the current extent of sweetgrass or the variability of the species along stretches of shoreline. So some habits of sweetgrass gathering have changed and may affect weavers’ sense of the condition of the stands.

Thornton (2008:147) discussed the effect of changes in technology on “the limits of production and the conceptualization of time, space, and place.” He asserted that canoes, “as a means of negotiating the land and seascape[, were] integral to people’s understanding of place.” The features of different canoe types were determined by the functions they served and the conditions in which they were used, all of which were tied to the environment. In addition, places could have special value because of the presence of cedar trees that could be used to make canoes and other objects. Constructing a canoe meant creating a new being, for the canoe itself was alive (Thornton 2008:148). Using materials from the land and sea strengthened the connection with the landscape, and evidence of past use became “signatures” of the ancestors. Life was sustained in multiple ways through “communion with place” (Thornton 2008:147). Arguably, without canoes, the experience and meaning of place is substantially altered.

That is not to say that life without canoes is not of value or that cars prevent meaningful experience in the landscape. Bowcutt (2015:30) asserted that the shift to car travel in the twentieth century represented an adaptive change that helped preserve cultural practices. Writing about Native Americans in California, she explained that using cars enabled gatherers to reach remaining tanoak trees and maintain traditions in the face of diminishing acorn production. She rejected the idea that indigenous people are “static” and presented changes in tools and transportation as responses to “the new cultural landscape” (Bowcutt 2015:31). So, the shift from canoes to cars can be regarded as an effective way of adapting to changing conditions, but it also affects the experience of and in the landscape. More specifically with respect to sweetgrass, access to stands is limited by reliance on car transportation. As a result, awareness of stands, the experience of gathering, and harvesting pressure have become focused on two access points at a single site in Bowerman Basin.

6. Defining places functionally rather than strictly geographically

Having historicized the sweetgrass harvesting practices and gathering grounds, I argue that Thornton's (2008:10) formulation of "place = space + experience + time" requires some modification under these circumstances in order to guarantee the access to resources that land-use and occupancy mapping is intended to support. First, places such as gathering grounds serve a function. Rather than fixing that function at a specific point in space, an emphasis on function allows for the possibility that the function shifts in space as the result of natural ecological change and/or ecological response to anthropogenic impacts. In a sense, the change becomes part of the experience that "makes places," and places are defined functionally rather than strictly geographically. Second, in the altered landscape, the time that "makes places" may be shorter than what might characterize unaltered landscapes (though effects of colonialism may still exist in a seemingly unaltered landscape). In other words, a shift of gathering practices in the last fifty or one hundred years might make sense in an altered landscape, whereas a much longer timeframe might be appropriate in an environment that is less physically disturbed. Knowledge derived from experience "within living memory," i.e., within a person's lifetime (Tobias 2000:35), can represent several generations back because of what was passed on to the current generation from grandparents; and that knowledge likely incorporates adjustment to or accommodation of significant changes that have occurred over multiple decades.

C. Analysis: Following Sweetgrass through Time and Space in Four Watersheds

1. Environmental history and cultural geography

The sweetgrass stands of Grays Harbor provide an example of a shifting resource that is followed by the weavers. Using charts, maps, aerial photos, official descriptions of the landscape, first-person accounts of weavers, I trace sweetgrass gathering grounds from earliest historic times to the present and show that despite – or because of – changes to the landscape, the weavers have followed the sweetgrass. Examples of shifts are found in four watersheds or sub-basins, with all "roads" (sometimes literally) leading to Bowerman Basin (Figure 3-4). The primary focus is on the mouth of the Hoquiam River and Rennie Island, which I assert are likely historic gathering grounds, and Bowerman Basin, the gathering grounds of today. The shoreline and tidal flats in this portion of Grays Harbor have been modified a great deal by hundreds of acres of fill, to which the sweetgrass seems to have responded by migrating westward. I then more briefly trace shifts in sweetgrass gathering from the Humptulips River/Chenois Creek area to gathering in Bowerman Basin as a result of human displacement, decreased access to coastlines, and change in transportation from canoes to cars. Next, I review the change in gathering grounds from the Skokomish River delta to Bowerman Basin, which was brought about by watershed alterations created by hydropower and agriculture, and possibly overharvesting. Finally, I examine Willapa Bay, where sweetgrass quality has been affected by competition from an invasive species and, possibly, the herbicides used to control it. Last year, Shoalwater tribal members made the trek to Bowerman Basin to secure the sweetgrass they needed, providing another example of weavers following the sweetgrass.

Shifts in gathering grounds in these four watersheds have resulted from a variety of factors that affected the environment and lifeways of the people. Taken as a group, these shifts result in a convergence of gathering effort (and harvesting pressure) on Bowerman Basin. This area is not only where significant stands of sweetgrass have grown since at least the 1950's (James and Martino 1986:74) but also where a major regional highway runs closest to the intertidal marsh, making that area accessible via modern transportation in a way that other areas are not (personal observation). With these shifts, a prevailing view that sweetgrass was on the decline developed among weavers. Within Bowerman Basin, however, stands have been expanding in recent decades. At the same time, some localized areas have experienced decrease in stem height, erosion of stands on the waterward side, and encroachment by willows on the landward side. Thus, the foundation is laid for both "yes" and "no" answers to the question, "Is sweetgrass on the decline?"

2. *Hoquiam River Delta, Rennie Island and Bowerman Basin: Tidal flats filled*

The environmental history of the Hoquiam River, Rennie Island and Bowerman Basin is presented through evidence in historical maps, government surveys, botanical records, published histories of the area, observations by area residents, historical photos, aerial photos, and my field work. The cultural geography of sweetgrass is based on the experience of weavers as documented in reports for the Corps of Engineers, anthropological literature, collections of museums and historical societies, and informal interviews. Visual forms of evidence are presented in roughly chronological order in Figures 3-8 through 3-31 and are worth reviewing before the following text to get a sense of the major landscape alterations in this area over the last century and a half.

- **1841 – 1859 Earliest documentation of marsh at the mouth of the Hoquiam River but not along shoreline west to Point New**

To reconstruct where sweetgrass historically grew in Grays Harbor, we turn to the earliest document available of the Grays Harbor area. (The Vancouver Expedition documented Grays Harbor in 1792 but did not document shoreline vegetation (Figure 3-8). The U.S. Exploring Expedition, commanded by Navy Lieutenant Charles Wilkes, created a chart of the area in 1841 (Figure 3-9). (Charts were created for ship navigation purposes and focus on waterbodies, intertidal areas, and shorelines.) The chart shows extensive marshland at the mouth of the Hoquiam River. A lobe marked "Spar Point" may refer to abundant driftwood collecting in the delta, which is consistent with the meaning of the name "Hoquiam" (or "Hokium"), or "hungry for wood" (Van Syckle 1982:56). (Spars are wooden poles made from tree trunks and include masts, booms and yardarms to which sails are attached on ships.) A similar condition was documented half a century earlier in the map created in 1792 by Joseph Whidby of the Vancouver Expedition: "Trees aground" is the notation added in the "Dry at low water" zone in the general location of the mouth of the Hoquiam River (Capoeman 1991:95; Figure 3-8). Brackenridge Bluff runs west of the mouth of the Hoquiam along the shore to Point New. Much of this shoreline will become highly modified and part of Bowerman Basin a century later, but there is no marsh shown along this shoreline in 1841. A channel in the mud flats at the location of the future Grays Harbor City indicates stream input from what would have been a forested ravine that is visible – following logging – in an 1889 photo (Van Syckle 1982: unnumbered photo plate;

Figure 3-13). No marsh is indicated at this location in the 1841 chart, but it is the western-most of two main access points to gathering grounds of today.

In his chronicle of Midshipman Henry Eld, Jr.'s journey from Puget Sound to the Black River and down the Chehalis River to Grays Harbor, Wilkes includes this description of forested shoreline and occasional salt marsh (Volume V of *Narratives*, as cited in Van Syckle 1982:43-44):

> "The spruce forest extends down to the water's edge, except in a few places around the harbor where there are patches of salt marsh, which produced coarse grasses and cat's-tail (*Typha*). The salt creek [sic] into which the tide flows are generally very tortuous; and the meadows are occasionally overflowed at spring-tides."

The "coarse grasses" of salt marshes probably included *S. pungens*, which, as an erect bulrush with "edges" produced by its triangular cross-section, can be described as a coarse grass.

Surveys conducted during 1858-9 by the U.S. General Land Office (GLO) for the purpose of establishing boundaries and subdivisions of public land, included these observations of the mouth of the Hoquiam River:

> In the eastern part [of Township 17 N, i.e., mouth of Hoquiam River] – along the bay there are some tide prairie [sic], which are not often overflowed, especially about the mouth of the Hokium [sic] & also considerable open bottomland covered with grass, some thickets of Willows, Crabapple, etc., which might be easily cleared and which seldom overflow. (GLO, 1858, Field notes for T 17N R 10W S 11 & 12, p. 407)
>
> Land south of 68 chains [from base of steep hill to the Hoquiam River and bay shoreline] level tide bottom subject to inundation by tides one or two feet. North part hilly . . . . Timber Spruce & Hemlock. Undergrowth Willow, Crabapple, Sallal etc. with considerable open grass tide land. (GLO, 1859, Field notes for boundary between T 17N R 9W S 7 & T 17N R 10W S 12, p. 379)

The shoreline west of the Hoquiam River was described as follows:

> North of the bay there is a ridge one or two hundred feet in hight [sic] extending East & West across the Township. Near the bay, along the western part of the

> township it is steep and precipitous . . . . (GLO, 1858, Field notes for T 17N R 10W S 11 & 12, p. 407**)**

So tidal marsh is present at the mouth of the Hoquiam but not along the steep shoreline to the west that eventually becomes part of Bowerman Basin.

Native Americans lived in and gathered resources in this area. A Native American headman, Molasses Doctor, lived with his family near the mouth of the Hoquiam (Van Syckle 1982:253). In 1859, a camp was located in the delta on what is called Spar Point in the Wilkes Expedition chart, presumably because of the driftwood that collected in this river with a name meaning "hungry for wood" (Van Syckle 1982:56; see Figure 3-9). This camp was the site of potlatches, gatherings of cultural significance, so the people of the bay were clearly familiar with the area (Van Syckle 1982:253).

Additional descriptions of the mouth of the Hoquiam in the 1860's appear in *The River Pioneers: Early Days on Grays Harbor*, which was written by Van Syckle (1982), a retired newspaper reporter and editor who based his work on newspaper articles of the time, letters, government records and documents, and other primary resources. Van Syckle (1982:250) described the vegetation structure and tidal influence in this delta area: "[B]elow the bluff, there was a treeless space . . . . On both sides of the Hoquiam near its mouth was considerable prairie-like open area, littered with tide-carried drift." He also noted that on the east side of the river mouth was located a large Native American cedar-plank house. This structure confirms that indigenous people, variously called Cakokiams, Hokeum, and Hoquiams, dwelled near the mouth of the river and would have had access to resources in the marsh. These are among the Hoquiam people that would have been counted by the Indian Agent for annual reports to the U.S. government. In 1886, Willoughby reported 16 total Hoquiam, a number greatly diminished from more robust populations by small pox epidemics post-contact with Europeans (Willoughby 1886:237). Using an epidemiological approach to estimating original populations in the Pacific Northwest, Boyd (1999:264) determined that, in Grays Harbor, populations before contact were probably ten times the number that remained in the 1880's.

Accounts of flooding in the Hoquiam delta provide a sense of the amount of freshwater contributed to the inner bay by this watershed. In the 1860's, early European American inhabitants of the Hoquiam flats were faced with floods that carried away a grindstone attached to inconveniently buoyant wood, cattle escaping rising flood waters by standing on the flared bases of Sitka spruce trees at the edge of the tide flats, and loss of animals in sloughs and intertidal mud (Van Syckle 1982:251).

Between the mouths of the Hoquaim and Chehalis Rivers, and receiving their salinity-lowering inputs of freshwater, lies Rennie Island (Figure 3-14). A later survey described "grass" that was likely *S. pungens* on what was then recorded as Renie's Island*.* More detail about Rennie Island is provided in the 1891-1895 section of this chapter; some is provided here to complete a picture of the Hoquiam River delta and the likely presence of sweetgrass before human activities significantly altered the shoreline.

- **1882 City of Hoquiam grows out over the marsh at the mouth of the Hoquiam River**

The economic base of the future City of Hoquiam began to take shape in 1882 when Emerson's lumber mill began operation (Van Syckle, 1982:256). The milled lumber was used to plank roads on the tidelands, and even the sawdust byproduct served as fill to raise streets above high water (Van Syckle 1982:179, 262). The technique continued to be used for decades, and a 1908 photo of street construction shows criss-crossing layers of wooden components required to raise the planked streets above the tide-soaked marsh (Van Syckle 1982: unnumbered plate; Figure 3-11). A photo from c. 1891 captures the railroad tracks and City of Hoquiam expanding out over the marsh (Figure 3-10).

- **1889 No marsh along shoreline at base of slope west of Hoquiam or at stream entering bay near Grays Harbor City wharf**

By 1889, the construction of a railroad bed westward out of Hoquiam was propelled by dreams of Grays Harbor City, which would overlook and benefit from commercial activity at a mile-long deepwater wharf. A photo of that year shows the railroad work proceeding at the base of the steep forested slope (Van Syckle 1982, unnumbered plate; Figure 3-12). Although the shoreline would have been modified by cut-and-fill and some land-clearing efforts, no sign of marsh vegetation is evident in the tidally flooded area at the base of the slope. If marsh were present, we would expect to see emergent vegetation above the surface of the water, even at high tide. The absence of intertidal vegetation is not surprising because the geomorphology of tidal marshes is typically characterized by a gradual slope, which creates the space for marsh to establish at hospitable elevations. Another photo from the same year was taken from higher elevation in the clearcut ravine, which would have hosted a stream that flowed into the bay at the site of the current westernmost sweetgrass harvesting grounds. The channel formed by that input is visible in Wilke's 1841 chart described earlier. (Farther west along the shoreline is Breckenridge's Bluff, indicated in the 1841 Wilkes Expedition chart and shown in more dramatic relief in a 1909 photo (Figures 3-9 and 3-16).)

In a cultural report for the Corps of Engineers in association with its dredging efforts, James and Martino (1986) focused on the Grays Harbor City area as the location of the historic, as well as current, harvesting grounds. Based on their interviews with weavers and gatherers, the authors deduced that the area was a gathering ground before 1889, but they could not determine what happened to the sweetgrass during the short life of Grays Harbor City. They hypothesized that "[t]he present sweetgrass site either started after the city disappeared, or, more likely, the grass simply survived the short life of the boomtown." It is possible that sediment from the logged hillsides was washed downstream to the edge of the bay and that accumulated sediment inputs facilitated the establishment of new marsh, including sweetgrass. Since we do not have evidence of marsh at this location in the 1889 photos, what seems even more likely is that sweetgrass was gathered in the general area but not at the location of the Grays Harbor City wharf. At this time, harvesting could have occurred in remnant marshes of the Hoquiam tidelands or at nearby Rennes Island (see previous and next sections). Use of canoes would still have been prevalent, so identification of and access to existing stands would have been relatively easy to accomplish, perhaps even a matter of course (Van Syckle 1982:279). Other areas mentioned by James and Martino are the south shore of Grays Harbor, where small stands of *S. pungens* are still found in creek outlets and the Elk River delta (personal observation), and the North Bay area, where extensive stands are still found along relatively unaltered shorelines between the mouths of the Humptulips River and Chenois Creek, at Grass Creek, and at Point New (personal observation, Figures 3-34 and 3-35). Moon Island was also mentioned by one weaver as the "traditional" harvesting ground (James and Martino 1986:72), but that island was created on the mudflats in the early 1900's with dredged material (Figure 3-20) before being converted to a World War II airstrip (Figures 3-21 and 3-22). So it does not seem likely that weavers were harvesting at Grays Harbor City wharf, but sweetgrass was probably available and therefore harvested in the general area.

Jerry Brown (personal communication), a resident of the Hoquiam area, had visited Bowerman Basin since 1950; and his memories are consistent with the lack of marsh in the 1889 photos of the railroad construction at the base of the hillside and at the Grays Harbor City wharf site. We spoke at the old wharf location in 2005, and he contrasted the conditions at that time to what had existed decades before. He said that the beach in this area used to be 10-15 feet lower, meaning that sediment had accumulated in the years since. His recollection draws attention to the process of sediment build-up that could lead to the establishment of intertidal vegetation along the highway and west of the wharf site decades later.

- **1891 – 1895 Marsh vegetation is found on Rennie [Renie's] Island near mouth of the Chehalis and Hoqiuam Rivers and at Point New**

Conducted in 1891, a General Land Office survey described marsh vegetation on nearby Rennie Island (then recorded as Renie's Island), between the mouths of the Hoquiam and Chehalis Rivers. The intertidal area was platted after having been diked with piling and an earthen berm and claimed by its aspiring owner, and was described as follows:

> The land is almost entirely level; no portion rising to a height of over 20 inches. The soil is a rich alluvial deposit from the streams and rivers entering Gray's harbor [sic], and deposited by the action of the tide currents. There is no timber or brush found on the island, but it is every where covered with a growth of grass about 4 ft. high which is common to tide flats. All the land is covered by the very highest tides

> to a depth of perhaps 2 ft. but this occurs only a few times during the year. (GLO, 1891, Field notes for T 17N R 10W S 13, p. 435)

Based on the proximity to freshwater flows, the alluvial deposits, the intertidal elevation, and especially the height (approximately 120 cm) and erect habit of the plant, the "grass" in this area would likely have been *S. pungens.* This survey was conducted on June 30, 1891, so approximately 80% of the total vertical stem growth would have occurred (Crandell, unpublished data). Average stem height might therefore reach 150 cm by the end of August, the peak of the growing season. Sweetgrass of that height is found in quadrats of relatively low June salinity (0-7 ppt, average of 3 ppt) (see chapter on the response of sweetgrass to environmental factors). Low salinity levels would be characteristic of deltaic islands so close to the mouth of both the Hoquiam and the Chehalis. McGee (1978:4) described average salinity as 5 ppt in winter and 20 ppt in summer on the upstream end of this island, which is where the marsh is located in the 1985 chart. McGee's salinity data were based on a U. S. Army Corps of Engineers (USACE) (1977:23) report that also states that groundwater inflows from the Chehalis River provide substantial freshwater inputs to the estuary and could lower salinities in tidal flats (USACE 1977:20). In addition, field work conducted on the island in October 1999 revealed an array of plant species typical of intertidal areas in Grays Harbor, with *S. pungens* being common at lower elevations, though nowhere taller than 70 cm (Crandell, unpublished data).

The vegetation on Rennie Island was depicted in a U. S. Coast and Geodetic Survey chart published in 1895, after the GLO survey was completed (Figure 3-14). The island is visible in the distance in a panoramic photo of Hoquiam taken in 1910 from a hill overlooking the town (Figure 3-17).

Another major marsh area is shown in the 1895 chart at Point New, the westernmost end of the north shore in the inner bay (Figure 3-14). A much later report for the Corps of Engineers stated that *Scirpus americanus* (now *S. pungens*) occurred here in low-salinity patches within a lagoon-like area dominated by freshwater species (Smith et al. 1976:F-49, F-51). At Grass Creek, a nearby site to the north, *S. americanus* is one of only five species listed in that same report as having appeared in sampling quadrats, along with *Carex lyngbyei, Deschampsia cespitosa, Distichlis spicata*, and tiny *Lilaeopsis occidentalis* (Smith et al. 1976:F-120). (The western shore of the North Bay was apparently difficult to characterize in general terms because portions of this report are slightly inconsistent. (See the Humptulips section in this paper and the characterization of low silty marsh on this coastline (Smith et al. 1976:F-75, F-76, F-77, F-78; Figure 3-26).)

- **1892 First formal documentation of sweetgrass in Grays Harbor**

In *Flora of Washington*, Piper (1906) refers to a specimen of *Scirpus americanus* (Persoon) collected in Westport, which is located in the southern outer bay of Grays Harbor. (*S. americanus* (Persoon) is presented by Piper as being synonymous with *Scirpus pungens* (Vahl), which was described by Vahl in 1805 in Copenhagen as part of his attempt to clarify some misunderstandings about European species in Linneas's work (Jorgensen 1999:53). The variety of this species that occupies the North American Pacific Coasts is formally called *Schoenoplectus pungens* (M. Vahl) Palla var. *badius* (K. Presl) S. G. Smith, which was originally "discovered" in Peru and then later in Monterey, California (Smith 1995:100).)

Small stands of *S. pungens* still exist on the eastern shores of this bay and the delta of the Elk River, though diminished within the city limits of Westport (Weinmann, personal communication; Dethier 1990: 33; personal observation). Piper based his flora exclusively on specimen collected in Washington, including those collected by Henderson in 1892. Piper refers to Henderson's collection as private, though Henderson was on the University of Idaho faculty and director of its herbarium, and his collection formed the basis of the UI herbarium's collection. Piper would have had access to Henderson's specimen, but a fire in 1906 destroyed much of the collection, presumably including this sample and rendering it unavailable for examination on the website of the Consortium of Pacific Northwest Herbaria (http://pnwherbaria.org/). Nevertheless, documentation of the specimen in Piper's flora provides evidence that *S. pungens* was found in Grays Harbor at the end of the nineteenth century.

- **1900-1911 Hoquiam delta marsh is diminished as City of Hoquiam grows out over the tidelands**

As the city of Hoquiam grew, the delta was altered and intertidal marsh filled in. As mentioned earlier, a photo from c. 1891 captures the railroad tracks and City of Hoquiam expanding out over the marsh (Figure 3-10). In 1901, a horseless carriage (steam bus) traveled planked roads and sawdust streets, the latter creating the necessity for the occasional push from passengers (Van Syckle, 1982:262). A 1908 photo shows "[w]orkers planking Hoquiam streets above the high-water level" using crisscrossing layers of logs and timbers over vegetated ground (Van Syckle 1982, unnumbered plate; Figure 3-11). The caption of a 1911 photo of Aberdeen explains that "[p]lank streets and side-walks kept traffic out of the swamps" (Van Syckle 1982: unnumbered plate). Accumulated driftwood that caught the attention of both the Indigenous people that named themselves and the river and early explorers is visible at the edge of the grounds of the Hoquiam Hotel, which was built on fill over the marsh (Figure 3-15).

- **1870's – 1920's Generations of weavers gather sweetgrass in Grays Harbor**

Accounts of weavers gathering sweetgrass in Grays Harbor are found in a variety of sources. Some are individuals who can be placed in time; other accounts refer to multiple generations of weavers using a particular site. The use of a site by multiple generations can be understood in two ways, and it is important to tease apart time and place: 1) multiple generations have gathered at a particular site over time, with one generation passing the knowledge of plant and place onto the next generation; or 2) multiple generations have collected contemporaneously at a site, in other words, within a particular time frame.

Descendants of Jennie Krise, a Snohomish/Tulalip woman who lived in the Kamilche/Skookum Inlet area of South Puget Sound, described her seasonal rounds gathering wild blackberries, catching chum salmon, picking oysters and cranberries, and gathering sweetgrass in Grays Harbor (notes of Krise's great-granddaughter and grandson housed at the Mason County Historical Society in Shelton, Washington, as cited in De Danaan 2013:66, 277). Krise was 22 years old when, in 1874, she married an older European American man originally from Ohio and probably gathered sweetgrass in Grays Harbor before that date since she would have learned as a young girl about gathering grounds for important materials. Krise likely gathered sweetgrass in Grays Harbor up to the time she died in 1909, or had others gather it for her as her mobility dwindled. (Krise may also have been aware of and returned to the sweetgrass stands known to her parents in the Skokomish River delta because they lived there possibly as captives before the Treaty of Point Elliot required freeing all slaves in 1855. By the late 1920's, Skokomish stands were diminished due to agricultural modifications from dam construction, diking and tilling, perhaps in combination with overharvesting (James and Martino 1986:75, Nordquist and Nordquist 1983:13). (See section on the Skokomish River delta.)

A number of weavers stated in the 1980's that generations of their families had harvested sweetgrass at Bowerman Basin. This is where we need to be careful about assumptions regarding time and place. Generations of Katherine Barr's family stretching back to her great-grandmother, Mary Heck, gathered sweetgrass in Grays Harbor (James and Martino 1986:74). Barr was Quinault but lived on the Chehalis Reservation. When interviewed at the age of 65 in 1985, she stated that she, her mother and great-grandmother had used the Bowerman Basin site, which was the only site considered accessible at that time. Allowing a conservative estimate of 20 years for the start of each generation, her mother would have been about 20 and gathering sweetgrass in 1920, and her great-grandmother would have been about 20 and gathering sweetgrass in 1880. In the case of Barr's family, some of the generations would have used the Bowerman Basin site at the same time, but – since we don't have evidence of marsh at Bowerman Basin before 1950 (see Hazel Pete's memory) – it appears that they would also have been among the weavers following the sweetgrass from stands in the Hoquiam River delta or Humptulips River/Chenois Creek area (the latter being closer to the Quinault reservation, as explained in a later section), and eventually to the Bowerman Basin site. Similarly, multiple generations of Hazel Pete's family (Chehalis and Skokomish) have gathered sweetgrass in Grays Harbor (James and Martino 1986:74). Hazel was 71 years old when interviewed in 1985, so her mother and grandmother would have been gathering in Grays Harbor as far back as 1895 or even earlier.

In the early 1900's, Ella Frank lived with her mother at the mouth of the Humptulips in the northern outer bay of Grays Harbor and gathered weaving materials including sweetgrass in the area (James and Martino 1986:75). Sweetgrass currently grows in the mouth of the Humptulips, and extensive stands grow southeast of the Humptulips along the eastern shore of the northern outer bay to Chenois Creek and resumes at Grass Creek. Given the herbarium specimen collected in 1892 in Westport in the southern outer bay, it is reasonable to assume that sweetgrass stands were growing in the Humptulips area in the 1890's. Frank later moved to Bay Center in Shoalwater (or Willapa) Bay, where some small stands of sweetgrass can be found today (Fred Weinmann, personal communication; Rick Pratt, personal communication; personal observation). Hazel Pete noted that a small stand near Tokeland in Shoalwater Bay hosted only shorter stems rather than the full variety found in Bowerman Basin (James and Martino 1986:74). (See section on Willapa Bay.)

Sweetgrass does not grow in the homewaters of the Hoh Tribe, and Hoh weavers traveled to the Grays Harbor for sweetgrass after a road to the Quinault Reservation went in (James and Martino 1986:76). A highway map dated 1915 depicts a road from Quinault to Hoquiam (Capoeman 1991:133, Figure 3-18), so gathering sweetgrass in the area by the Hoh would have occurred at least that long ago. Since the road appears to hug the shoreline where the Chenois Creek stands are found south of the Humptulips, the road may also have made possible gathering in that area.

Nellie Ramirez (Squaxin/Skokomish) (1906-2003) started making baskets at 10 years of age and moved to the Quinault Reservation after marrying when she was 16 years old (Willis 2003:16). During a weaving demonstration in 2000, she described creating coiled baskets entirely out of sweetgrass when she was younger (Ramirez, personal communication). Once at the Quinault Reservation in 1922, the Hoquiam stands would have been the likely source of sweetgrass, though it is also possible that sweetgrass was harvested in the Humptulips-Chenois Creek marsh. (See also Humptulips/Chenois Creek section.)

The anthropologist Thelma Adamson conducted ethnographic work with the Chehalis in 1927, on their reservation upriver in Oakville. She reported that sweetgrass "came from the [Grays] harbor, where it grew in the mud and was gathered in during the months from July to September" (Miller 1999:44).

Louise Pulsifer (Skokomish) explained in 1970 that the Skokomish estuary used to support sweetgrass stands, but that after the tide flats were diked and plowed in the late 1920's, the remaining remnants were sparse and too short to be of use (James and Martino 1986:75). This decline led to Skokomish weavers shifting their harvesting to Grays Harbor. They first followed a trail to the Satsop watershed and then canoed down that river to the Chehalis and then out to the bay (Elmendorf 1993: 29, 31). Eventually, this trip was aided by the automobile (Nordquist and Nordquist 1983:13). (See also Skokomish section.)

- **1928 Nautical chart shows an expanding Hoquiam, vegetation on Rennie Island, and the first indication of dredged material disposal on the tide flats**

In the 1928 version of nautical chart #6195, the Hoquiam delta is built out and wharfs other port facilities are seen extending out over the tide flats. Vegetation is still indicated on Rennie Island. For the first time, deposition of dredged material is depicted on the mud flats that will become Moon Island and the airport strip over the next two decades.

- **1936 Hoquiam River delta has been filled in and built over, and little marsh is visible**

An aerial photo taken in 1936 for the U.S. Army Corps of Engineers reveals that the Hoquiam River delta had been built over by the expanding town of Hoquiam that extended from the bay on both sides of the river to some distance up the river channel (Figure 3-20). The intertidal area between the edge of the city development and the deepwater channel that is filled at low water is marked by wharfs and railroad spurs, dikes and dredged material (some of which is contained within dikes and other deposits on mudflats that are not contained), some buildings or covered areas along a wharf, some shrubby vegetated patches (characterized by circular patches). The only sign of possible marsh vegetation can be seen at the western edge of the city in a “corner” created by the relatively unaltered shoreline and a dike constructed perpendicular to the shoreline. This “corner” may have represented either a remnant of the original Hoquiam marsh or the early migration of the marsh along the shoreline in response to being “pushed out” of the original delta. Some marsh, including sweetgrass, probably also existed on the other side of the dredged channel at Rennie Island, just outside the frame of the photos.

- **Late 1930's Sweetgrass is harvested on Moon Island, which was created with dredged material.**

In a letter written in 1983 to the Grays Harbor Regional Planning Commission commenting on the Grays Harbor Estuary Management Plan Draft Environmental Impact Statement, Marian Susewind stated, "The south shore of Moon Island was the traditional area for collecting the grasses, however, since the advent of the airport, the access (other than by boat) is long and dangerous" (James and Martino 1986:72). The history of Moon Island may surprise some people: it was created with sandy substrates dredged from shipping channels, and the deposits are visible on the mudflats in the 1936 aerial photo (Figure 3-20). The sandy substrates would have been favored by sweetgrass (Dethier 1990:33), and the species probably established on these dredged material islands, as it later did on the end of the airport spit and nearby Half Moon Island (personal observation). With the addition of more fill, these manmade "islands" were transformed into the airport, which was constructed at the beginning of World War II.

Sweetgrass still grows in some mixed stands on the south side of the airport, but security and safety concerns at the airport preclude access from shore, leaving boat access as the only option (James and Martino 1986:72). The mixed stands farther to the east are accessible from the road running along the (artificially created) shore, but these stands would not be expected to have the appeal of those pure stands in Bowerman Basin (personal observation).

- **1950 Hints of marsh are visible on south side of the airstrip and causeway and on the north shore of Bowerman Basin**

The “corner” marsh described in 1936 is no longer visible in an aerial photo taken in 1950 (Figure 3-22). By this time, wharfs had been reconfigured along the west end of the Hoquiam waterfront, and an Army Air Corps airstrip had been constructed on fill deposited on the mudflats in 1941 (Grays Harbor Refuge Planning Team 1990:14; Figure 3-21). The airstrip was connected to the mainland via a causeway. On the south side of the causeway and airstrip, driftwood may have accumulated in some “traps,” and the remnants of piles of dredged material can be seen. The combination of driftwood and dredged material could well have hosted sweetgrass, as can be observed today on the south side of the airport. Although the “corner” marsh is gone, some hints of intertidal vegetation appear along the north shore of what was becoming Bowerman Basin by virtue of the airport and causeway. In 1985, Hazel Pete (Chehalis) expressed familiarity with sweetgrass in Bowerman Basin in the 1950’s, when she was about 40 (and later noted expansion of the stands in subsequent decades through the 1980’s) (James and Martino 1986:74).

The 1957 topographic map published by the U.S. Geological Survey depicts a fringe of intertidal vegetation on the north shore of Bowerman Basin, but it ends just east of the airport trestle piling (Figure 3-28). No intertidal marsh is documented west of this point, including at the location of the Grays Harbor wharf. However, additional intertidal marsh is present on the south side of Bowerman Basin (i.e., north side of the airport strip) and on at least the western (downstream) end of Rennie Island.

Jerry Brown (personal communication), a resident of the Hoquiam area with whom I spoke in 2005, had visited Bowerman Basin since 1950. He said that the vegetation, which he called “grass,” used to extend on the north shore only to the airport trestle. We spoke at the site of the old Grays Harbor City wharf, and he contrasted the conditions at the time of our conversation to what had existed decades before. He said that the beach in this area used to be 10-15 feet lower, meaning that sediment had accumulated in the years since. His memories are consistent with the lack of marsh in the 1889 photos at the base of the hillside and at the Grays Harbor City site (Figures 3-12 and 3-13), and they help explain the process of sediment build-up that could lead to the establishment of intertidal vegetation at that site and along the highway decades later.

- **1960's Sweetgrass harvested along north shore near railroad trestle to airport**

Florine Shale-Bergstrom (Quinault) (personal communication) started harvesting sweetgrass in Bowerman Basin for her grandmother around 1960 when she was 8 or 9 years old. (She shared this experience in 2001, when she was 51 years old.) Near the site of the old Grays Harbor City wharf (i.e., western access point in the wildlife refuge, where Highway 109 swings away from the shore and up a ravine), her nephew was cleaning sweetgrass stems harvested from a popular stand west of the access point. Florine said that when she first started harvesting, her family gathered sweetgrass "around the corner," referring to the stands near the other access point near the railroad trestle pilings that extend across the bay to the airport spit.

- **1974 – 1978 Intertidal vegetation has established along the north shore of the basin and around the expanded airport and remains on the wide fringes of Rennie Island**

Bowerman Basin – Eastern End of North Shore

In an aerial photo taken in 1974, intertidal marsh is clearly visible along the north shore of the basin west to the filled area at the base of the trestle used to transport material to the original airstrip (Figure 3-25). There is also a patch at the location of the old Grays Harbor City wharf, where State Route 109 swings northwest and up a ravine away from the shore (Figure 3-13). Vegetation below the high tide line is also visible on the northern and southern shores of the airport.

Marsh vegetation was surveyed in an undiked area along the north shore of Bowerman Basin in July and August 1975 as part of a study assessing impacts of deposition of dredged material on wetlands, including succession of marsh species in filled areas (Smith 1976:F-viii, F-x; Figures 3-26 and 3-27). (Inadequate records of deposition of dredged material since 1940 limited the researchers' ability to quantify impacts on a bay-wide basis (Smith 1976:F-101).) *Carex lyngbyei* and *Scirpus americanus* (now *Schoenoplectus pungens*) were found in patches were freshwater inputs flowed into the tidal area (Smith 1976:F-48). However, these patches were found to be smaller than one acre in aggregate, were deemed "inconsequential," and were therefore not mapped in detail (Smith 1976:F-66; Fred Weinmann, personal communication). The relevance of this work to the current study is that *S. pungens* was not a dominant species, so extensive stands would not have been present on the north shore of Bowerman Basin east of the railroad trestle.

Nevertheless, it appears that this area is where Charles and Elizabeth Peck, a forestry extension agent and musician who lived with the people of Queets on the Quinault Reservation, documented harvest of sweetgrass on the north shore of Bowerman Basin in the early 1970's. In the script for a slide presentation on gathering and weaving with sweetgrass, they described the location and process of harvest, and Charles Peck's photographs show gatherers on the north shore of Bowerman Basin (Peck and Peck 1977, Shebitz and Crandell 2012:164; Figure 3-23). Emily Miller (Twana) and Louisa Pulsifer (Skokomish) were also photographed gathering sweetgrass in Bowerman Basin in the 1970's (Nordquist and Nordquist 1983:11; Figure 3-24). So even if the sweetgrass patches were not large enough for the scale of the Corps of Engineers' study, they were known to the local weavers.

Bowerman Basin - Grays Harbor City

A few years later, a site along the highway near the Grays Harbor City access point was considered as a potential location for the deposition of dredged materials in an effort to create more marsh in intertidal areas (also known as "beneficial use" of dredged material) (McGee 1978:1). Using the dredged material to create marsh was a deliberate change from depositing that material *on top of* marsh to raise it above the reach of the tide and "reclaim" the land from the sea. The new practice came about as ecosystem services of tidal wetlands became better understood and the loss of low marsh was considered undesirable (Smith 1976:F-101) . A botanical survey in support of the marsh-creation efforts provided detail about the Grays Harbor City site (McGee 1978):

> This site is very close to the highway, allowing easy access for construction equipment and the public. The marshlands which presently exist at this site are limited to a thin shoreline fringe. There is a distinct floral zonation with the upper community dominated by *Carex lyngbyei* and the lower community composed mainly of *Scirpus americanus* [now called *Schoenoplectus pungens*].

Other intertidal species found in this area were *Cotula coronopifolia, Deschampsia cespitosa, Distichlis spicata, Triglochin maritimum,* and *Potentilla pacifica* (now *Potentilla anserina*).

The presence of some freshwater wetland species indicated some overland or groundwater inputs of freshwater. *Scirpus americanus (Schoenoplectus pungens)* was one of four species recommended for planting on the dredged material, and the recommended elevation range for this species was 7.5-8 feet above MLLW. This range was based on existing vegetation in the area, which was "very limited in extent" and "sparse," but now the elevation range over which sweetgrass is found is on the order of at least one meter (McGee 1978: 22, 25; personal observation). The site was described as being exposed to heavy wave action, which does not tend to favor development of marsh vegetation, but can be tolerated by *S. pungens* (McGee 1978:22). One disadvantage to the Grays Harbor City site as a location for marsh creation was the anticipated widening of S.R. 109, which runs along the edge of the wildlife refuge. By 1998, the highway had been widened, an extensive stand of *S. pungens* had established next to the riprapped edge of the roadbed, and a large stand of sweetgrass just west of the access point was a preferred harvesting ground for some weavers (B. L. Ryan, personal communication, 1999; S. T. L. Ryan, personal communication; personal observation).

Rennie Island

Rennie Island, where sweetgrass stands near the mouth of the Hoquiam River existed since at least the late 1800's, was also the subject of study in the 1970's. The small island that was surveyed in 1891 by the General Land Office was enlarged with dredged material, with the center having been "used, until recently, as a settling pond for paper mill effluents" (McGee 1978:3). A botanical survey was conducted to aid in the evaluation of the east and west ends of Rennie Island as sites for marsh creation (McGee 1978:1).

Sweetgrass (then called *Scirpus americanus*) was found at both ends of the island and was among the dominant species on the upstream eastern end where salinities were lower (McGee 1978:3-4). (The downstream "western end" of the island was actually a discontinuous area of dredged material that was added as a revision in 1983 to the 1957 USGS topographic map (Figure 3-28). According to the McGee survey, it hosted greater plant diversity than the east end or the Grays harbor City site, but based on the species present, that diversity would seem to have been a function of drier conditions on sandy substrate and/or at higher elevations. Cowardin classification code applied to this area in the 1981 National Wetlands Inventory map included the water regime modifier "infrequently flooded" (Grays Harbor Refuge Planning Team 1990:D-15). A field visit via kayak and on foot in 1999 confirmed the presence of *S. pungens*, along with *Carex lyngbyei* and other species typical of nearby marshes in Grays Harbor, but the largest stand of sweetgrass (a triangle approximately 50 meters long with a 30-meter base) was on the downstream western end of the island, not the discontinuous site described above which is now partially forested (personal observation). The maximum height of sweetgrass stands was 50 cm. Gone were the four-foot tall coarse grasses surveyed by the GLO, underscoring the degree to which this island has been altered since 1891.

- **1984 More vegetation above and below the tide line establishes with the deposition of uncontained fill in the basin**

In an infrared aerial photo taken in 1984, more vegetation above and below the tide line had become established as the east end of the basin was filled in with uncontained fill (Grays Harbor Refuge Planning Team 1990:14). The intertidal vegetation was expanding along the shoreline between the pilings from the trestle to the airport and the Grays Harbor City wharf fills.

In an interview in 1985, when she was 71, Hazel Pete (Chehalis) stated that the sweetgrass appeared to be expanding westward along the shore, including past the Grays Harbor City wharf (James and Martino 1986:74). She further remarked that the stand was larger than she had seen in the 1950's. This pattern is consistent with the expansion visible in the aerial photos.

- **Mid-1980's By this time, Bowerman Basin was the only sweetgrass site that weavers considered accessible in Grays Harbor**

When James and Martino (1986:74) interviewed quite a few weavers in the early to mid-1980's, Bowerman Basin was emphasized as the most important sweetgrass gathering ground. The stand was large enough to be able to withstand harvesting by multiple weavers (though some local weavers would later express concern about overharvesting), and the variety of stem sizes provided multiple options for weavers, who would use different stems sizes for different types of projects. These advantages were said to have contrasted with a small stand near Tokeland on the north shore of Willapa Bay (James and Martino 1986:74). In addition, Bowerman Basin was accessible via a highway.

Some weavers did know of the possibility of sweetgrass stands on the western shore of the North Bay between the Humptulips River and Chenois and Grass Creeks, but they did not consider these stands to be accessible. Here, the point is worth making that these stands are accessible today by boat or via a hike along the hummocky shoreline but are not accessible by car and public road (personal observation). Private property along the shoreline also prohibits access from the shore near Grass Creek (personal observation). Some patches in the South Bay are also considered inaccessible, though they can be reached by boat. James and Martino (1986:72) noted that sweetgrass stands were known at that time along the south shore of the harbor, and Nordquist and Nordquist (1983:13) stated that Skokomish weavers sometimes traveled to gathering grounds near Bay City after stands in their homewaters were depleted. The south-shore stands that would have been most accessible by road are at Bottle Beach State Park at Ocosta near Bay City (personal observation). Weavers could have found other stands at Johns River, Newskah Creek, and O'Leary Creek, with the greatest abundance having been at Johns River in 2000 (personal observation). (Marshes in the south bay that are characterized by *S. pungens* were also found at Andrews Creek and the Elk River, according to Dethier's (1990:33) classification of estuarine habitats in Washington State.)

Bilhaam ne'ex Loa Ryan (Ts'msyen) (personal communication, 25 July 1999) spoke of first harvesting in the westernmost (Grays Harbor City) stand of sweetgrass in 1984 and remembered stems "over her head," or approximately 160 cm tall. This height is no longer true of that particular stand but is characteristic of newer stands that had established farther west as of 2008. So the height that Loa remembers may be an indicator of the relative newness of the stand she originally harvested in the mid-1980's.

- **1990 Intertidal vegetation development appears to continue**

In an infrared aerial photo taken in 1990, the expansion of intertidal vegetation appears to continue (Figure 3-30). It should be noted that in this photo the tide was near its high-water mark, which limits the assessment of intertidal vegetation. However, in the

1994 revision of the 1957 USGS topographic map, intertidal marsh is depicted along the north shore, extending possibly as far west as the airport trestle location. (Some unevenness in the hatching used for marsh introduces some uncertainty in the extent of the marsh.)

- **1998 Intertidal vegetation on north and south shores of Bowerman Basin is visible and similar to current distribution**

In an aerial photo taken in 1998 for the Washington State Department of Transportation, the distribution of intertidal marsh is similar to the present, except for the subsequent expansion of sweetgrass westward of the Grays Harbor City wharf fill (Figure 3-31).

- **2001 Expansion of stands since 1960 noted by Quinault gatherer**

in 2001, when she was 51 years old, Florine Shale-Bergstrom (Quinault) (personal communication) explained that she had harvested the stands near the railroad trestle pilings leading to the airport for years, but that year she and her nephew harvested in the westernmost stands (near the Grays Harbor City wharf), which are reached via an access point where the highway swings away from the shoreline and up a ravine. She said that the westernmost stands were “new to us this year.” The awareness of new sweetgrass stands is consistent with the expansion of the stands described by Hazel Pete in 1985.

- **2007 Sweetgrass stand observed expanding farther westward along the north shore**

Observations during a 10-year study from 1999-2008 detected an expansion of sweetgrass stands westward along the north shore, well past the historic Grays Harbor City wharf location and a well-known harvesting area. In 2007, the ninth year of the study, the expansion was so noticeable that a new transect was added to the monitoring study.

- **2008 Ten years of monitoring documents overall expansion and, in some locations, stem height increase, but evidence of decline in quantity and quality in other locations**

The evidence presented in previous sections indicates overall expansion of sweetgrass stands in Bowerman Basin since at least the 1950's. So we might conclude that sweetgrass is not on the decline in the popular harvesting grounds. However, erosion of stands has occurred in a portion of shoreline that includes the most frequently harvested area near the old airport railroad trestle. Quadrats were established in 1999 along transects oriented perpendicular to the shoreline and parallel to the elevation gradient (see Methods section in Chapter 1). The quadrat at the lowest end of the transect was placed 1 meter up-elevation from the waterward edge of the stand. In a portion of the northern shoreline, these lower quadrats were eroded and became denuded: TN4-A and TN5-A were eroded in the second year of the study; TN6-A was eroded in the third year of the study; and TN7-A was eroded in the seventh year of the study. This erosion on the waterward side of the stands occurred in areas, especially TN4 and TN5, frequented by harvesters. This evidence supports the weavers' perception of a decline of sweetgrass in this area. Other disruptions have occurred at the high end of the sweetgrass stand at TN5-E, where some of the tallest stems can be found. Rafts of driftwood sometimes settled onto the marsh here and prevented growth for up to four years. In the last two years of the study, the quadrat was taken over by *Bidens* sp., rice cut grass, *Potentilla anserina*, *Eleocharis palustris*, jewelweed, and water parsley, and then buried by a combination of sandy sediment, sweetgrass wrack, and wood chips. Willows are also encroaching on the marsh in this area. Taken together, the changes at the upper and lower edges of the marsh in this popular harvesting area fuel the perception of a shrinking stand, which is supported by the evidence.

Stem height is the most commonly mentioned aspect of quality. For instance, B. L. Ryan (Ts'msyen) (personal communication, 1999) reported that stems in Bowerman Basin used to be over her head around 1984 but were no longer, and that was a major cause for concern. To determine if there were trends in stem height, regressions were conducted on data collected at individual quadrats from 1999 to 2008 (see methods in Chapter XXX). Increases are reported for analyses resulting in a statistically significant positive association between stem height and time (Crandell, unpublished data). Heights fluctuated from year to year, and there were rarely steady increases in height owing to annual variation and the methodology that requires yearly adjustment of sampling positions and measures only the maximum height within a sampling quadrat. The changes in height reported here are based on field measurements rather than the model determined by the regression analysis.

From 1999 to 2008, stem heights were found to be positively associated with time in two quadrats at low elevations of a transect along the highway: at TN3-A and TN3-B, stem heights increased from 107 and 106 cm, respectively, to 130 and 131 cm, respectively (TN3-A, p-0.017, R^2=0.53; TN3-B, p=0.009, R^2=0.60). Positive associations also were found at three quadrats on the north shore near the inner part of the basin: at TN7-B, height increased from 86 to 116 cm ($p=0.036$, $R^2=0.44$); at TN8-C, height increased from 114 cm to 128 cm ($p=0.003$, $R^2=0.69$); and at TN8-D, height increased from 129 to 167 cm ($p=0.046$, $R^2=0.45$). This last quadrat was at the upper edge of the marsh and became shaded by willows growing farther out over the herbaceous marsh species each year. The sweetgrass in this quadrat was growing in the shade of the willow canopy, and stems were longer and proportionately thinner than some of the tallest stems in other portions of the marsh. These longer, thinner stems are typically also supple, which makes them especially desirable to weavers (B. L. Ryan, personal communication, 1999; James and Martino 1986:73, 76). They are sturdy and do not break during weaving, and they are more easily trimmed lengthwise for uniform size (B. L. Ryan, personal communication, 2008a, 2008b). Suppleness of a number of plant species seems to be associated with shaded conditions (see Nordquist and Nordquist 1983:13 for beargrass, *Xerophyllum tenax*, and Turner et al. 1983:79 for slough sedge, *Carex obnupta*). In the final year of the study, *S. pungens* had given way to *Carex lyngbyei* in TN8-D, which indicates greater freshwater influence and a decrease in salinity that could also explain the increased height in this quadrat (see Chapter 1 for effect of salinity on plant characteristics).

Elsewhere in Bowerman Basin, stem heights were found to decrease over time. Statistically significant negative associations between stem height and time were found at TN1-C, where maximum height dropped from 125 to 104 cm ($p=0.002$, $R^2=0.71$). This quadrat is in a stand near the old Grays Harbor City wharf that is a popular harvesting area. Therefore, perceptions of decline in sweetgrass quality, as determined by stem height, are supported by the evidence. Decreases in stem height were also found at two quadrats on transects along the highway: height at TN2-C, a relatively low-elevation quadrat, decreased dramatically from 170 to 117 cm ($p=0.001$, $R^2=0.72$); and at TN3-D, a middle-elevation quadrat, stem height decreased from 110 to 81 cm ($p=0.031$, $R^2=0.46$). Finally, on the south shore, a decrease in height was found at TS2-D, a quadrat at the highest elevation in the basin ($p=0.006$, $R^2=0.063$). This quadrat is on an exposed shoreline at the western end of the airpot, with substrates of nearly pure sand that has built up over the course of the study. The decrease in height seems to be a response to burial and drier conditions (see Chapter 1 for effects of environmental conditions).

So in some parts of Bowerman Basin, sweetgrass has increased in height; but elsewhere it has decreased, most notably in one location that is a popular harvesting spot near the old Grays Harbor City wharf. Sweetgrass stands have expanded westward along the northern shoreline, but in the most frequented harvesting location, the stands are shrinking from erosion of the waterward edges of the stand and disturbance on the upper edge of the stand. Some of these data were collected in areas that are regularly harvested and support the statements by some weavers that sweetgrass is on the decline. So the answer to the question “Is sweetgrass on the decline?” depends on one’s perspective and is both “yes” and “no” in Bowerman Basin.

3. Humptulips River, Chenois Creek & Grass Creek: Displacement and change in access and transportation

The Humptulips River, Chenois Creek, and Grass Creek flow into the North Bay of Grays Harbor, which is located in the outer bay west and north of Bowerman Basin. Extensive stands of sweetgrass currently exist along the shoreline between these freshwater inflows, especially between the Humptulips delta and Chenois Creek (personal observation; Figure 3-33 and 3-34). This western-facing, exposed shoreline is relatively unaltered in this portion of the bay, so it is reasonable to imagine similar expanses of sweetgrass growing there in the past (Borde et al. 2003:1109; Figure 3-35). As stated earlier, Henderson's specimen collected in 1892 in Westport in the south outer bay confirms the presence of *S. pungens* in the bay during the nineteenth century (Piper 1906).

However, the abundance of sweetgrass may be a more recent development. In a report for the Corps of Engineers, Smith et al. (1976:F-91) categorized the shoreline from the Humptulips to Point New as "low silty marsh" (Figure 3-26). This marsh type was described as 50-100 m wide and characterized by coalescing circular clones of *Triglochin maritimum* and *Salicornia virginica* with *Carex lyngbyei* and *Deschampsia cespitosa* joining at higher elevations (Smith et al. 1976:F-75, F-78). *Scirpus americanus* (now *S. pungens*) was found only where freshwater influence was pronounced, such as at the mouth of a creek or at Point New in a lagoon hosting primarily freshwater species (Smith et al. 1976:F-49, F-51, F-66, F-78). A limitation of the 1976 study was that the survey site closest to the Chenois Creek stands was at the mouth of the Humptulips and was looked at qualitatively rather than quantitatively (Smith et al. 1976:F-17, F-18), so it is possible that more sweetgrass was present in the North Bay at the time than was reported in this study.

Local flora can be revealed in basketry materials. The Polson Museum in Hoquiam displays a twined sweetgrass basket made in 1910 that is attributed to the Quinault tribe, whose homeland is north of the Humptulips watershed. Since sweetgrass does not grow in the Quinault River delta, weavers would have had to gather it somewhere else, or traded for it. The Quinault had seasonal fishing sites in Grays Harbor at the Humptulips, Chenois

Creek, and the Hoquiam River, so gathering sweetgrass could easily have been part of their seasonal rounds in this area (provided they had secured the appropriate permissions from Grays Harbor tribes) (Hajda 1990:503).

At the time of the first European American settlement, the northern outer bay seems to have been one of the most populated and active areas of Grays Harbor, despite waves of small pox and other epidemics that decreased population by ninety percent after 1803 (Boyd 1999:265). So the use of sweetgrass was likely common here. In 1857, Mary Shephard, the daughter of English immigrants, visited a large village at "Chanoos Creek," where she saw women weaving baskets and mats and probably using sweetgrass for the former (James and Martino 1986:67). It was from this village that Chief Chinoose (after whom Chenois Creek is named) ventured in 1872 with a group of seventy Humptulips to deliver a message to R. H. Milroy, the Superintendent of Indian Affairs for Washington Territory (Milroy 1872:335). Milroy had asked tribes from Grays Harbor to meet him at the Chehalis Reservation on the Chehalis River in Oakville so that he could distribute blankets, cloth and other goods provided by the government. That reservation of a few square miles was established in 1860, despite the refusal of the tribes in this region to sign a treaty. Chinoose and his people would not accept the goods for fear that they would be interpreted as payment for the Humptulips land. Instead, Milroy (1872:335) reported,

> they wanted nothing from the Government but a paper that would enable them to hold their land against white men who were threatening to drive them away from it. I told them to come to the reservation with their people, where there was plenty of room and good land for all. They replied that that was not their home; that they had always lived at the mouth of the Humtolop [sic] and Chinoose Rivers, where their fathers had lived and died from time immemorial, and they wished to live and die there; that they did not know how to live away from salt water, where they could always get plenty of fish and clams.

Milroy further reported that "all the land around the bay on both sides of the mouth of the Humtolop . . . and up both sides of that river for miles, has been sold to mostly non-resident speculators" (Milroy 1872:336). Still, for several more decades the North Bay was an area of bustling Native American activity, according to Amanda Slover Fry, wife of Charles Fry, who was brought as an infant to Grays Harbor from Illinois in 1851 (James and Martino 1986:50; Van Syckle 1982:122, 165). Adamson (1927, as cited by James and Martino 1986:68) mentions a large potlatch house near the mouth of the Humptulips. Ella Frank, who lived near the mouth of the Humptulips until 1921, remembered large gatherings near Chenois Creek (James and Martino 1986:75).

Timber companies and saw mills were among the earliest arrivals and claimers of land in the region (Van Syckle 1982:349). Aided by the government through General Land Office surveys and policies that encouraged homesteading, private landowners acquired more and more land (Figure 3-26). As a non-treaty tribe, the Humptulips never got the paper they sought for any portion of their homeland, and they were displaced from their homelands over time (Van Syckle 1982:64, 349). According to Indian Agent Willoughby's 1886 report, the Humptulips numbered 16 and were described as growing crops and raising cattle (Willoughby 1886:239). Some of the Humptulips moved to the Quinault Reservation (Marino 1990:171, 175). Others moved to the Chehalis Reservation after all. Photos taken by Edmond Meany in 1905 document the family heritage of Chehalis Reservation residents: George Quinotle's father was Humptulips and moved to Chehalis Reservation but made clear that he missed his homeland (Meany 1905, Negative NA1158); Lena Heck's father was from Humptulips (Meany 1905, Negative NA1157). Still others lived as long as was feasible in the Humptulips-Chenois watersheds as individual homesteaders, working at lumber mills and in lumber camps, harvesting oysters and working for oyster companies and other fisheries, providing transportation and communication services for white settlers, working for white farmers and conducting limited farming of their own, and hunting and fishing and gathering plants when and wherever they had access (Willoughby 1887; Van Syckle 1982:59-60, 164, 168, 227, 253, 269; Capoeman 1991:106; Marino 1990:172; Crawford O'Brien 2013:75).

Individuals living off the reservation numbered among what became the "landless tribes of Western Washington" (Marino 1990:171, Bishop and Hansen 1978:23). In 1916, Special Allotting Agent Charles E. Roblin of the Bureau of Indian Affairs was based in Hoquiam for the purpose of reporting on Native Americans of Western Washington that were not enrolled at any agency (i.e., associated with reservations) and who had therefore not received any of the benefits stipulated in treaties (Bishop and Hansen 1978:26, Roblin 1919a). He was also tasked with accepting applications for adoption into the Quinault tribe at a time when adoptees would become eligible for allotments on the Quinault Reservation (Roblin 1919b). In the Grays Harbor region, the Quinault recognized the Humptulips, Grass Creek, Wynooche [sic], Lower Chehalis, Georgetown (Shoalwater Bay), Willapa and Lower Chinook as tribes affiliated by blood (Van Syckle 1982: 57). However, Roblin organized his report using fewer tribal names for the landless indigenous people in the area: Chehalis, Chinook, Quinaielt [sic], Satsop, Shoalwater Bay, and Wynookie [sic] (Roblin 1919b). Humptulips and Grass Creek may have been included in Chehalis or Quinaielt. In any case, some in the Humptulips/Chenois Creek/Grass Creek area likely found their way to the Quinault Reservation through this process of adoption.

As dislocation proceeded and disease took many lives, the use of canoes on Grays Harbor decreased; the heretofore common sight of Native Americans paddling canoes on the bay became uncommon (Capoeman 1991:101, 106). (See earlier section on canoes.) In addition, transportation modes were changing regionally. By 1915, segments of roads that would become today's State Route 101 were being improved by counties and the State and connected Quinault and Humptulips to Hoquiam (Capoeman 1991:133; Figure 3-18). Humptulips weavers could have traveled by wagon and eventually car to the Hoquiam area (Van Syckle 1982:350).

Weavers from reservations north of Grays Harbor along the Washington coast traveled to the bay for sweetgrass. The Quinault had fishing sites within the north bay and could readily have collected sweetgrass while in the area (Hajda 1990:503). They may also have visited the shoreline west of Hoquiam, i.e., adjacent to the future Bowerman Basin, especially once a road went in after 1915. Nellie Ramirez (Squaxin/Skokomish) (1906-2003) started making baskets at 10 years of age and moved to the Quinault Reservation after marrying when she was 16 years old (Willis 2003:16). During a weaving demonstration in 2000, she described creating coiled baskets entirely out of sweetgrass when she was younger (Ramirez, personal communication). Once at the Quinault Reservation in 1922, the Humptulips/Chenois Creek stands or the future Bowerman Basin would have been the closest sources of sweetgrass.

Sweetgrass does not grow in the homewaters of the Hoh Tribe, who live north of the Quinault. Hoh weavers traveled to the Grays Harbor for sweetgrass after the road from the Quinault Reservation to the harbor went in (James and Martino 1986:76, Capoeman 1991:133). A highway map dated 1915 depicts a road from Quinault to Hoquiam, so gathering sweetgrass in the area by the Hoh would have occurred at least that long ago (Figure 3-18). It is not clear whether the Hoh weavers were thinking of Chenois Creek or Hoquiam area when referring to "Grays Harbor." Either is possible, although the modern roadbed and railbed, which align with the originals, do not hug the Chenois Creek shoreline as closely as they do the Hoquiam (Figure 3-33). So to the degree that canoes were used upon arrival at the Humptulips or Chenois Creek, or weavers joined Quinault at fishing sites, sweetgrass stands in those areas would have remained accessible.

4. Skokomish River Delta: Hydropower, agriculture & overharvesting

Weavers were harvesting sweetgrass in the Skokomish tidal marsh until the 1920's, when impacts from agriculture and overharvesting are blamed for the decline of sweetgrass in this location (Nordquist & Nordquist 1983:13, James and Martino 1986:75). However, major changes in the watershed hydrology resulting from dams and a diversion also contributed to the fate of these sweetgrass stands. As a result primarily of agriculture and hydropower, weavers lost their supply of sweetgrass on the Skokomish and began traveling via wagon and then automobile to Grays Harbor.

To provide power for the ambitious City of Tacoma, dams were constructed on the North Fork of the Skokomish River in 1926 and 1930 (Figure 3-37). A larger dam trapped water in Lake Cushman and a smaller one downstream in Lake Kokanee. These dams would, on their own, have altered the timing and volume of flows from the North Fork. But a power tunnel diverted water from the latter dam to Hood Canal, completely bypassing the lower portion of the North Fork and therefore depriving the main stem of the Skokomish River of a large portion of its historic flow (Figure 3-37). With the completion of the second dam and the diversion, the City of Tacoma had harnessed the power of all the North Fork flow but at the expense of any flow on which the North Fork and downstream delta depended. (Through a settlement between the City of Tacoma and the Skokomish Tribe, a watershed-wide restoration project has been undertaken, a part of which is restoration of monthly flows between 100 cfs and cfs 240 to mimic natural patterns and meet the habitat needs of fish (FERC 2009:5-6). The average annual flow of the North Fork was 847 cfs before the dam construction (Northwest Treaty Tribes 2008). By decreasing the water flow from the North Fork to the main stem of the river, the freshwater inputs, especially during springtime, would have been affected. Salinity would in turn have been affected, as would the species composition of the marsh and sweetgrass's response to it (see Chapter 1). So the 1920's was a decade of hydrologic disruption in the watershed and would over time result in increases in salinity and decreases in the height of *S. pungens* (see Chapter 1 for effect of salinity on stem height). This response is consistent with the reports by weavers that sweetgrass became short and sparse, as explained in more detail below.

In the 1930's, a more direct impact occurred in the river delta, with the diking of 200 acres of Nalley Island and conversion to agriculture of this and other tidal areas (Northwest Treaty Tribes 2008; Figure 3-38)). Bertha Visser recalled gathering sweetgrass on the tideflats for her mother, Lucey Allen, a Skokomish weaver that lived from 1856-1936 (James and Martino 1986:75; see photo of Ash'ka'blu (Lucy [sic] Allen) in Crawford O'Brien 2013:Figure 17). Allen would likely have had access to sweetgrass there until the last few years of her life. Another Skokomish weaver who was born in 1882, Louisa Pulsifer, recalled collecting sweetgrass in the Skokomish delta marsh until it was plowed under along with other marsh species behind/within the dikes (James and Martino

1986:75). The sweetgrass that seems to have remained or reestablished outside the dikes was sparsely distributed and, according to Pulsifer in a 1970 interview, not tall enough to be useful weaving material (James and Martino 1986:75). This description of scattered sweetgrass outside dikes is similar to that observed on Rennes Island in the Chehalis delta of inner Grays Harbor (personal observation; see section on Hoquiam River) (By contrast, substantial stands of sweetgrass have developed waterward of an extensive diking system in the Skagit River delta (Ewing 1986; personal observation)). Such sparse populations would not be abundant enough to provide a sustained source of material. Soft twined baskets made with sweetgrass were in high demand in the tourist market, which would have meant increasing pressure on the remaining stands (Nordquist and Nordquist 1983:2). If harvest practices continued after 1930 despite the insults absorbed from the dams, dikes, and plow, it is understandable that weavers would attribute further decline to overharvesting. However, overharvesting is probably best considered a secondary rather than primary cause of decline.

Following the sweetgrass to Grays Harbor was consistent with other travel patterns. The Skokomish were long in the habit of visiting the Humptulips people at Chenois Creek, among others. For example, in 1878, 20-year-old Frank Allen (Skokomish) followed a well-worn path to Grays Harbor. He traveled by horseback the short distance from the Skokomish basin to the headwaters of the Satsop watershed, from there by canoe down that river to the Chehalis River, and thence to the outer bay to see the Humptulips headman Chinoose (Elmendorf 1993: 29, 31). Sweetgrass was not in short supply on the Skokomish in the 1800's, but with the arrival of the automobile, travel to the stands in Grays Harbor became even more convenient (James and Martino 1986:75). By 1915, roads that would become today's State Routes 101 and 12 connected Skokomish to Hoquiam, Humptulips and Quinault and provided routes for wagons and then automobiles (Capoeman 1991:133, Van Syckle 1982: 350, Figure 3-18). With the decline of sweetgrass, travel from Skokomish to the gathering grounds of Grays Harbor became more necessary.

For the last two decades, the Skokomish Indian Tribe has been engaged in efforts to re-establish stands of sweetgrass in their home watershed. As part of a multi-million-dollar watershed-wide effort to improve fish habitat and decrease flooding damage, tidal channels have been reconnected to the river and Puget Sound and dikes have been removed from Nalley Island (Figure 3-38). One of a number of goals is to re-establish intertidal marsh, with a particular focus on sweetgrass because of its cultural importance (DuBlanica, personal communication). Although reports of restoration of sweetgrass can be found in the mid-2000's based on an early project in 1999 (e.g., Middleton and Kusel 2007:170), more recent reports focus on fish habitat and mention the return of native marsh species only in a general way (Skokomish Watershed Action Team 2016:33, 35). Given that agricultural land typically subsides behind dikes and affects restoration potential or trajectory, it is possible that marsh re-establishment and species composition are affected by elevation (DuBlanica, as cited in Lamberson 1996; Frenkel 1992). (Lamberson (1996:23) seemed to assert that subsidence could cause loss of sweetgrass habitat, but subsidence occurs as land is *dried out* through prevention of tidal flooding. It is the exclusion of tidal waters and the tilling of the fields that would be major contributing factors to the loss of habitat and decline of sweetgrass.) Sweetgrass is most competitive and therefore dominates lower elevations in areas with coarser substrates and higher salinities. In a watershed as altered as this one, there is no guarantee that ideal conditions can be restored in support of the re-establishment of sweetgrass stands.

So sweetgrass has been on the decline for nearly 90 years in the Skokomish watershed due to agriculture, dams and diversion, and possibly overharvesting. This downturn in quantity and quality resulted in a shift of gathering grounds to Grays Harbor, especially as transportation became easier. Given the communication between neighboring tribes, it is also possible that – at least for a time – sweetgrass became a trade item between people of the Skokomish and Grays Harbor, as was known to have occurred between the Makah on the Olympic Peninsula and their linguistic cousins (Dididaht, formerly Nitinaht) on the southwestern coast of Vancouver Island, where sweetgrass was found in the estuarine marshes of the Cheewhat River and tidal Nitinaht Lake (Turner et al. 1983:2, 12, 82). With restoration efforts, sweetgrass may be returning to the Skokomish delta, but it remains to be seen whether or not the stands will become robust enough – and of desired quality – for the gathering grounds to shift once again.

5. Willapa Bay: Invasive plant species & herbicide control

Willapa Bay hosts sweetgrass stands today, and probably has as long as Grays Harbor, but a unique set of issues have bearing on the perception that sweetgrass is on the decline and on shifting gathering grounds. The stands are not as extensive as those in Bowerman Basin but remain a source of sweetgrass for members of the Shoalwater Tribe and the Chinook in Bay Center (Thompson and Marr 1983:24; James and Martino 1986:75; Tremblay 1990:39; Johnson 2013:6, 14; Johnson et al. 2013:201, 205; Kay Harradine, personal communication; Fred Weinmann, personal communication; personal observation). (The tribal staff refer to sweetgrass as “sweetgrass sedge” or “saltwater sedge,” probably to distinguish it from the other true grass species that are called “sweetgrass” across North America (Johnson 2013:14; Johnson et al. 2013:201, 205).) In the post-treaty era of the late 1800’s, Coast Salish weavers, such as Jennie Krise, lived in off-reservation communities at Kamilche and Oyster Bay in South Puget Sound, and may have traveled to Willapa Bay, as well as Grays Harbor, for sweetgrass (De Danaan 2013:66).

A century later, Shoalwater Bay Tribal Elder Anita [Shipman] Couture remembered Agnes James, an older neighbor on the reservation who “made baskets, [and] picked grass out in the bay in a rowboat” (Crawford O’Brien 2013:216, 362). Anita was writing in 1998 at the age of 65, and the timeframe of this memory appears to be before 1970. In the 1980’s, Willapa Bay was mentioned by Thompson and Marr (1983:24) as one of two areas where sweetgrass could still be harvested; by then it was thought to have disappeared from “pockets” around Puget Sound, leaving the coastal populations more valued than ever. In 1986, James and Martino (1986:75) noted that “Shoalwater Bay weavers have sweetgrass . . . in their own immediate area.” However, the quality was considered to be inferior to that in Bowerman Basin because there was not much variety in stem sizes, which would be used for different projects. The stand was said to be limited to fine stems (James and Martino 1986:74). Generally, weavers prefer stems that are long but relatively thin (Shebitz and Crandell 2012:166). This description of sweetgrass in Shoalwater Bay is consistent with what I observed at the site next to S. R. 105 in 2000; in the largest stand, the stems were about 80 cm tall and relatively thin (approximately 4 mm), not unlike many – but not all – portions of the stands at Bowerman Basin (personal observation). (It is important to note that requirements vary with the weaving project, and fine stems are preferred by some weavers. For her twining work, Anna Jefferson (Lummi) preferred the fine stems of Bowerman Basin to the more robust stems of the Nooksack River delta (Lamberson 1996:23).)

James and Martino (1986:74, 75) suggested that some Shoalwater weavers may have collected sweetgrass in the South Bay and along the South Shore of Grays Harbor. However, the consensus at the time of their report seemed to be that sweetgrass stands were not – or were no longer – accessible in those areas.

Even without the full range of sizes, Willapa Bay provided sweetgrass to weavers through the 1980's and 1990's. The poet and artist Gail Tremblay (Onondaga/Mic Mac) (1990:39), who lives in Olympia, Washington, published a poem about one such outing:

Gathering Basket Grass

for Mary Nelson

We stood in the muck on the edge
of Shoalwater Bay, the sun making
us sweat as we pulled up the grass
in bunches, triangular stems
popping as they were yanked loose
from the Earth which supports all life.
We bent and stood in rhythmic
motion thinking of our ancestors
plucking the ancestors of this grass
to make baskets, and as we dragged
the heavy bales up the rocks
to the road, we held the image
of the strength of grandmothers carrying
basket materials several miles home;
we held it in our minds. We threw grass
in the car trunk and drove up
the coast to wash off mud and sweat
in the surf before travelling [sic] inland.
Now, months have passed since I
sorted and stored these plants.
But every time I open the closet
the smell conjures an image;

> I stand with two other Indian women,
> my belly full of salmon, and harvest
> the fiber used to keep the ancient art alive.

The fact that the grass was pulled "in bunches" indicates that at least portions of the stands were pure enough that handfuls of stems could be pulled at a time rather than a more selective approach that would be required in a mixed stand (personal observation).

Today, sweetgrass stands are found next to S.R. 105, between Tokeland and Raymond, where the North River flows into the bay (Fred Weinmann, personal communication; personal observation; Figure 3-39) and on the west side of Long Island within the Willapa National Wildlife Refuge (Rick Pratt, personal communication; Figure 3-41). The stand by the highway is accessible by car (much like the stands on the north shore of Bowerman Basin); the population on the shores of Long Island is accessible by boat (Rick Pratt, personal communication). Tremblay's poem appears to refer to the S. R. 105 stand, based on the reference to hauling the bundles up the "rocks," which are only found next to sweetgrass where riprap blankets the roadbed of highways built within the reach of the tide (Figure 3-39). Sweetgrass is also found at the Shoalwater Bay Tribal Center in Tokeland (Nisbet 2012:30), but a non-native weaving instructor who teaches there described it as "very short, stunted, outcompeted by *Spartina*, and treated to all sorts of chemicals, both deliberate and run-off" (Harradine, personal communication). Harradine's description touches on several important issues that contribute to the sense that sweetgrass is on the decline.

First, problems in places like the Skokomish are well known (see previous section on Skokomish watershed), and by the 1980's, the consensus was that Willapa Bay was one of two remaining areas where the species could be harvested (James and Martino

1986:75). But Willapa Bay has been subjected to an invasion of *Spartina alterniflora*, an aggressive cordgrass native to the East Coast of the U.S. that grows at the same tidal elevation as sweetgrass (personal observation in Willapa and in Bowerman Basin). The original introduction occurred around 1890, but the expansion of cordgrass really accelerated in the 1980's (Feist and Simenstad 2000:272). This rapid spread prompted a major multi-agency control effort because of the potential impact on the oyster industry and on salmon and shorebird habitat (Feist and Simenstad 2000:267, Buhle et al. 2012:881). Mechanical and chemical control measures were employed (Major et al. 2003:8-9, Figure 3-40). Before that bay-wide control, small circular clones of *Spartina* were found growing next to sweetgrass at the S. R. 105 site in 1999 (personal observation). Harradine (personal communication) shared her observation about cordgrass outcompeting sweetgrass in 2002. (The shortening of the stems and the invasion by *Spartina* near the tribal center may be facilitated by the in-filling of North Cove, on the edge of which the reservation sits (USACE 2009:26-29, 96). Sedimentation in the cove increased as the barrier dune that creates the ocean side of the cove eroded and breached during winter storms in the late 1990's and early 2000's. The erosion is thought to be due to decreased sediment supply coming from the Columbia River, where dams prevent the transport of granular material downriver to the drift cells that feed the Washington coast (USACE 2009:27).)

Control of invasive species has ecological benefits but can affect neighboring species, especially in aquatic environments where targeting individual plants is particularly challenging. In 2006, Judith Altruda (personal communication), an artist living in Tokeland, observed that sweetgrass appeared to suffer following the application of herbicide to cordgrass in the area. By contrast, a resident of the Skagit River delta observed that the native marsh recovered well after herbicide treatment of *Spartina*, though he seemed to focus on species composition rather than specific attributes of one plant (Jim Gallup, personal communication). *Spartina*'s impact on sweetgrass remains a concern in Willapa Bay, according to Tony A. Johnson (2013:14), Cultural Committee Chair for the Chinook Tribe and Education Program Manager for the Shoalwater Bay Indian Tribe.

The potential effect of chemical substances on human beings, including weavers, cannot be ignored. *Smhayetsk* Teresa Ryan (2000:100; 2002; 2017), a Ts'msyen (Tsimshian) weaver who grew up in Washington and completed graduate work at Central Washington University, expressed concern that intimate contact with the materials exposed weavers to herbicides and other chemicals. In Willapa Bay, another chemical of concern has been a pesticide used on an industrial scale to improve conditions for cultivated oyster plots (Simenstad and Fresh 1995:47). There are three pathways by which exposure to toxins may occur: weavers first harvest the plant in the potentially contaminated marsh, then prepare the material and handle the dried stems while weaving, and often, for convenience, hold the next strand (for twining the weft) in their mouths. To the degree that water quality, substrate chemistry, or plant tissue are compromised with toxins, the weaver's health may be put at risk.

To address the issues of access, exposure to toxins, and stem quality, a number of weavers have tried growing sweetgrass in gardens or pastures, with mixed success (Ryan 2000:112; Harradine, personal communication). The September 2017 issue of the Shoalwater Tribe newsletter contains photos of at least seven Shoalwater members gathering sweetgrass at the Grays Harbor City site in Bowerman Basin, so the local Willapa

Bay material does not seem to be meeting the needs of the weavers of this tribe. We see again that weavers are following the sweetgrass.

D. Conclusion: Defining Gathering Grounds Functionally Rather than Strictly Geographically

The answer to the question “Is sweetgrass on the decline?” has ecological and cultural implications. Early in this study, the cultural answer was “yes,” but the ecological answer appeared to be “no.” Convinced that both must somehow be true, I set out to solve this mystery by using “two paths to knowledge [that are] rooted in the same reality”: western science and Indigenous knowledge (Mazzacchi 2006:466). I examined the environmental history of four watersheds and the cultural geography of the Native Americans who call them home. The answer that emerged is layered.

I began by establishing that culture is dynamic and that Native Americans have shifted cultural practices such as hunting and fishing in response to environmental changes. I have shown how cultural shifts followed environmental shifts when gathering grounds for sweetgrass shifted physically within Grays Harbor and surrounding watersheds. I found that on a regional level sweetgrass has been on the decline over the last century due to filling of tidelands, dams and water diversion, agriculture, invasive species and associated herbicide use – and possibly overharvesting of stands weakened by these factors – in Grays Harbor, the Skokomish River delta, and Willapa Bay. These environmental changes combined with cultural disruption in the form of displacement, exclusion from private property, and changes in modes of transportation led to reliance by multiple peoples on a single site in Grays Harbor. (Other forms of cultural disruption that interfered with the transfer of IEK included boarding schools, conversion from mobile lifeways to farming, and other forms of forced assimilation.)

Within the remaining gathering grounds at Bowerman Basin, the news is better: sweetgrass is expanding westward along the shoreline, migrating as it has since the founding of the City of Hoquiam. And the weavers have been following the sweetgrass for decades, shifting with the conditions. In a few locations within Bowerman Basin, the stems are lengthening. But in other locations, the stands are shrinking from erosion on the water side and willow encroachment on the upland site. Elsewhere stem heights are decreasing, perhaps from accretion of sediment, perhaps from changes in freshwater inputs. Some of these negative changes are occurring in the marsh at popular access points, where most of the harvesting occurs, and have therefore captured the attention of weavers. As gatherers venture farther from the current access points, they may find material more to their liking.

Documentation of usual and accustomed gathering grounds is especially challenging in Southwestern Washington, where treaty negotiations collapsed when tribes did not get assurances from the U. S. government that they could remain in their homelands and continue lifeways suited to the environment that they had occupied for millennia. Whether in the face of broken promises for treaty tribes or in the absence of treaties for so-called "landless tribes," documenting use and occupancy of the landscape is essential in asserting and maintaining rights (Tobias 2009:38, 50). Use-and-occupancy (UAO) maps are living documents that require updating because cultural practices must respond to environmental and anthropogenic changes Tobais (2000:xii). One map is equivalent to a chapter of a long history. But a series of these UAO maps, taken together, document the adaptability that Indigenous peoples have demonstrated for thousands of years. They become records of resilience. With this understanding of change and the need to adapt, gathering grounds should be defined or understood functionally rather than strictly geographically.

This functional approach applies to the current gathering grounds of Bowerman Basin. The environmental history of the Hoquiam River delta and associated tide flats tells us that the basin was created about seven decades ago and marshes developed along the northern shore only after that time. So if we focus on the geographic location, we do not have evidence of a century-old gathering ground. However, if we focus on the function, we widen our scope and can follow the sweetgrass along the shoreline as it responded to anthropogenic change. And we can see how the weavers have followed it to Bowerman Basin. Likewise, we can understand the impacts of human activities on other watersheds, such as the Skokomish, and see how sweetgrass stands were diminished, resulting in a shift of gathering grounds to Bowerman Basin. In watersheds that were less physically altered, such as the Humptulips, we can also see how cultural disruption changed access and Indigenous practices, including use of canoes, and again see why weavers shifted their gathering to Bowerman Basin. In Willapa Bay, a combination of ecological changes, i.e., the introduction of an invasive species and its chemical control, and changes in transportation have affected gathering grounds in Willapa Bay, and prompted at least a partial shift to Bowerman Basin. In other words, we can follow the sweetgrass and the weavers in the landscape and, by tracing these shifts, define gathering grounds based on their function.

While newer – or younger – gathering grounds might seem to have shallower historical roots, they are still meaningful places. In Thornton's (2008:10) formulation of "place = space + experience + time" for ancient cultures, we might expect time to be on the scale of centuries or even thousands of years. But, in altered landscapes and in the context of cultural disruption, shorter timeframes are appropriate. The definition Tobias (2000:35) applies for current use is “within living memory,” which refers to a person’s lifetime and is on the scale of decades. This scale appears to be what we are often working with when it comes to experience in sweetgrass gathering grounds. However, the use of sweetgrass spans and has been shared among generations, and these connections confer meaning upon modern day experiences and those gathering grounds that are accessible. As Tremblay (1990:39) wrote about a sweetgrass stand along a highway in Willapa Bay,

> We bent and stood in rhythmic
> motion thinking of our ancestors
> plucking the ancestors of this grass
> [. . . , W]e held the image
> of the strength of grandmothers carrying
> basket materials [. . .] in our minds.
> [. . .] I stand with two Indian women,
> my belly full of salmon, and harvest
> the fiber used to keep the ancient art alive.

Using a functional approach to define gathering grounds permits us to track adaptive shifts that are responses to environmental changes and cultural disruption. We also thereby acknowledge the resilience demonstrated by the Native American weavers who have followed the sweetgrass. Creation of UAO maps can be strengthened with other methods and practices. Long-term monitoring of sweetgrass stands would augment weavers’ testimonies and document changes to which they are likely to respond. Using canoes to travel to sweetgrass stands would provide access to longer stretches of shoreline and enable gatherers to select stems from a wider variety of characteristics than they may see near the trailheads in Bowerman Basin.

Living documents created with a functional approach serve as tools for protecting the rights of Indigenous people and preserving their access to resources, as called for in Article 29 of the *United Nations (UN) Declaration on the Rights of Indigenous People* (United Nations 2008:11; Salik et al. 2014:331):

> Indigenous peoples have the right to the conservation and protection of the environment and the productive capacity of their lands or territories and resources. States shall establish and implement assistance programmes [sic] for indigenous peoples for such conservation and protection, without discrimination.

The UN's Convention on Biological Diversity has produced its Global Strategy for Plant Conservation, which is regularly updated. A portion of the strategy's rationale emphasizes the connection between plants and Indigenous people: "(v) [T]he knowledge, innovations and practices of indigenous and local human communities that depend on plant diversity will be recognized, respected, preserved and maintained" (Convention on Biological Diversity 2002). The dependence of indigenous culture on the environment is underscored by Steve Pavlik, a professor at the Northwest Indian College in Bellingham, Washington: "Saving the culture begins with saving the environment" (Deloria 2012:160). The connection between culture and environment has meant survival and is therefore a matter of human rights for the Native Americans of the PNW. Environmental rights are cultural rights, and cultural rights are human rights. Ultimately, we find in this undertaking to protect human rights that "two paths to knowledge" converge to one.

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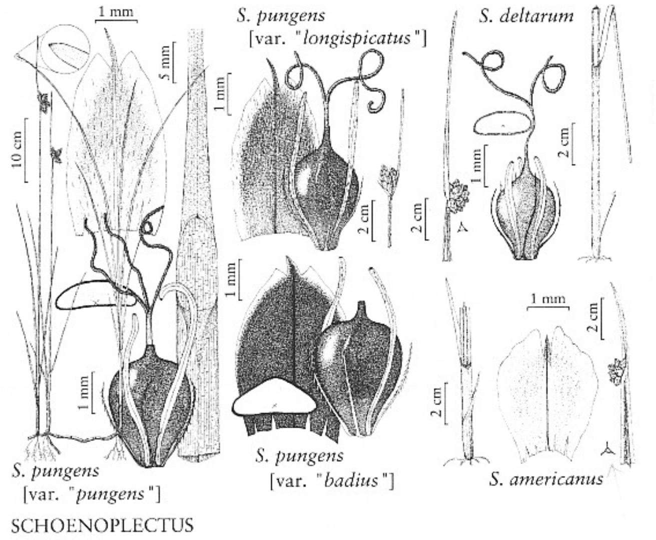


Figure 3-1. Top drawings of *Schoenoplectus pungens* (formerly called *Scirpus americanus* in the Pacific Northwest) by Jeanne R. Janish are from *Vascular Plants of the Pacific Northwest* (Hitchcock et al. 1969:372). Bottom drawings by Susan A. Reznicek are from the *Schoenoplectus* section in *Flora of North America: North of Mexico* (Smith (2002:51). *S. pungens var. badius* is native to the coastal marshes of the Pacific Northwest.

Figure 3-2. Harvesting sweetgrass. From upper left: Teresa Ryan (Ts'msyen) removing leaves from base of stem in the Skagit River delta (25 July 1999). Loa Ryan (Ts'msyen) selectively harvesting stems in the Skagit marsh (25 July 1999). Loui Chichinoff Thadei (Aleut) harvesting in Bowerman Basin (24 September 2000). (Photos: Caren Crandell)

Figure 3-3. Baskets made with sweetgrass. Top row: Loa Ryan (Ts'msyen). (Photos: Mitchell Almaguer-Bay) Middle row: Quinault. Bottom row: Louisa Pulsifer (Skokomish). (Photos in bottom two rows: Burke Museum of Natural History and Culture; object numbers 2.5E1149 and 2.5E1618, respectively)

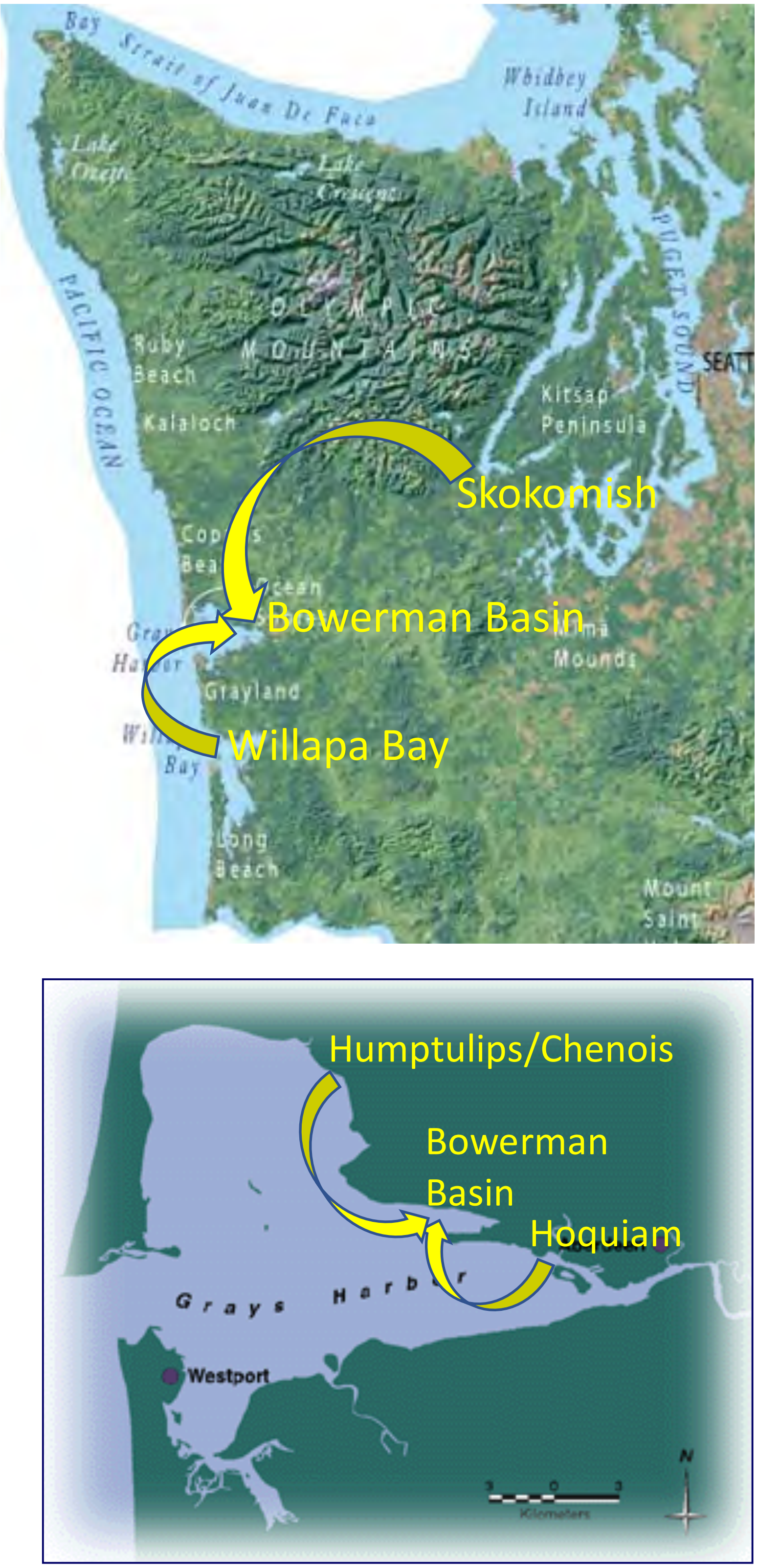


Figure 3-4. Shifts of sweetgrass gathering to Bowerman Basin from four watersheds covered in this study. (Map sources: www.bentler.us and Pacific Northwest Coastal Ecosystem Regional Study)

Figure 3-5. Cowichan woman using her canoe to transport tule gathered that was gathered nearby. Photo was taken on Vancouver Island by Edward Curtis in 1910 Title and caption: "Tule Gatherer – Cowichan. 1910. The manufacture of tule mats for use as carpets, house-walls, mattresses, capes, and sails is still in many localities an important duty of women." (Plate no. 315 in Curtis (1913))

Figure 3-6. Puget Sound women harvesting cattails over the side of their canoe (Thompson and Marr 1983:21). Photo was taken by Edward Curtis in 1912. Title: "Tule Gatherers – Puget Sound. 1912." (Plate facing page 112 in Curtis (1913))

Figure 3-7. Emily Miller (Twana) gathering cattails and poling her cargo-laden canoe home to Skokomish (Nordquist and Nordquist 1983:12).

Figure 3-8. Chart of a portion of the Northwest Coast of North America as documented by Joseph Whidby of the Vancouver Expedition in 1792, published in 1798. Inset of Grays Harbor is enlarged. This is the earliest Western documentation of the area. Hoquiam River delta is near notation "Trees aground" on north shore of inner bay. The description is consistent with the designation "Spar Point" in the Wilkes Expedition chart (see Figure XXX) and the name Hoquiam, which was understood to mean "hungry for wood" (Van Syckle 1982:122). Available from https://oregonencyclopedia.org/ .

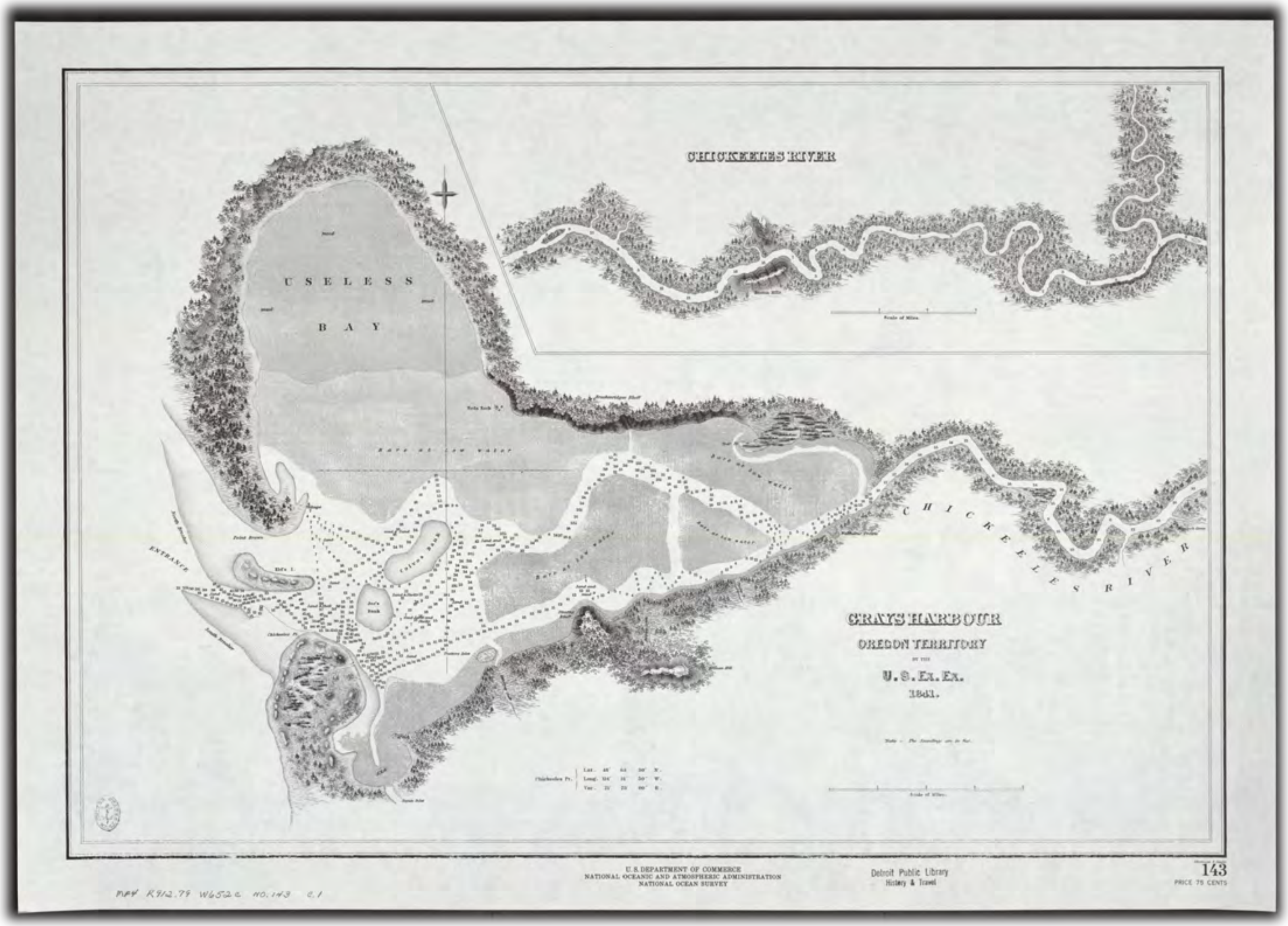


Figure 3-9. Chart of Grays Harbor and Chehalis River surveyed and drawn by Horticulturist W. D. Breckenridge of the Wilkes Expedition conducted in 1841. Note Spar Point (i.e., accumulated driftwood) and marshland indicated in Hoquiam River delta, as well as the bluff to the west, which was named after the horticulturist himself.

Figure 3-10. View looking west at railroad and City of Hoquiam spreading out over marshes of Grays Harbor, Washington, c. 1891. (University of Wahisngton Libraries, Special Collections, Order Number WAS0451, Negative Number UW4389)

Figure 3-11. Construction of streets in Hoquiam c. 1908, using planking necessary to keep them out of reach of high tides. (University of Washington Libraries, Special Collections, Order Number WAS0195, Negative Number UW348)

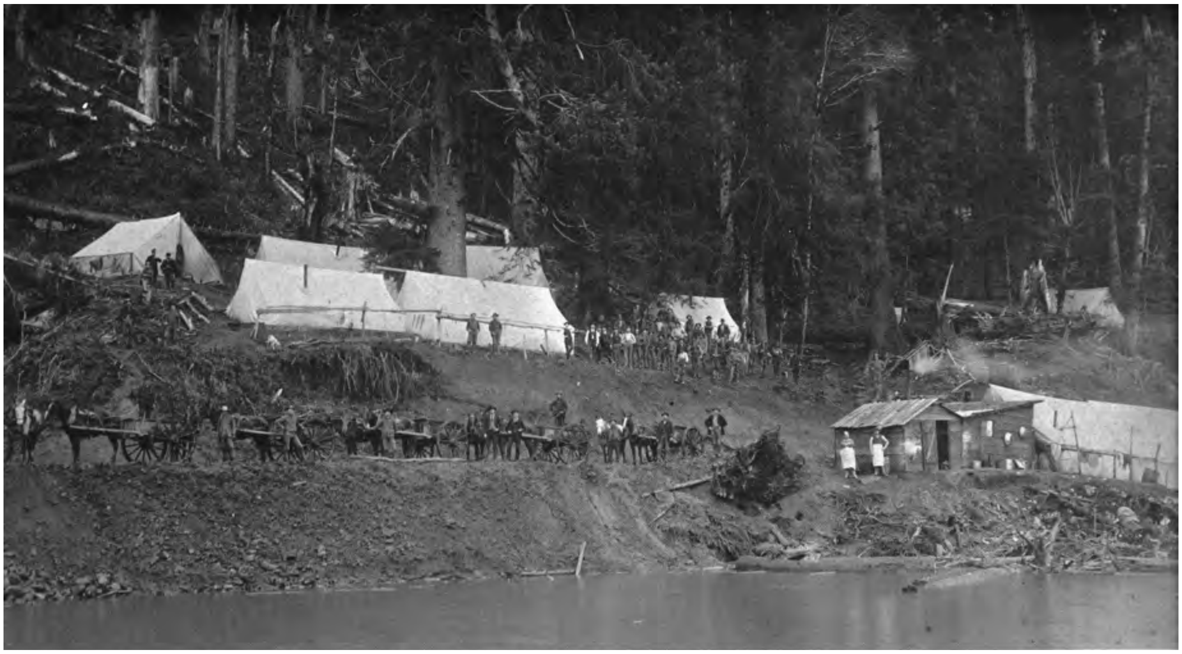
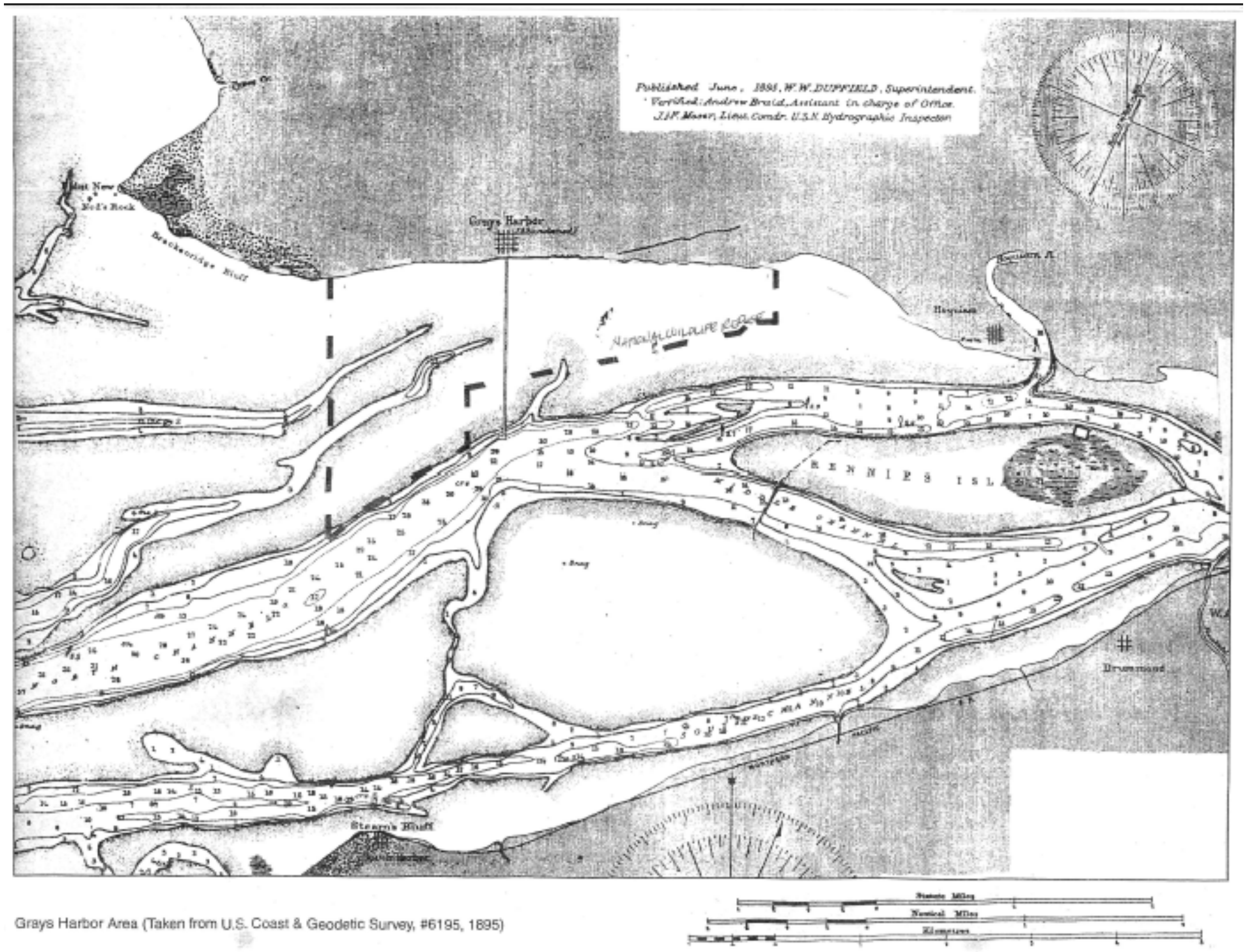


Figure 3-12. Early phase of construction of railroad from Hoquiam west to Grays Harbor City wharf in 1889. No marsh is visible at the base of the steep slope. (Unnumbered plate in Van Syckle (1982))

Figure 3-13. View of Grays Harbor City wharf on 19 August 1889 from of a ravine logged in anticipation of the establishment of a boom town serving rail and sea-going traffic. Wharf extends 1 mile to a deep-water channel. (University of Washington Libraries, Special Collections, Order Number WAS1276, Negative Number UW4363)



Grays Harbor Area (Taken from U.S. Coast & Geodetic Survey, #6195, 1895)

Figure 3-14. 1895 U. S. Coast and Geodetic Survey chart of Grays Harbor (#6195). Major marshes are indicated at Rennie [formerly Rennies] Island and at Point New but not in between. On Rennie Island, the 1891 GLO survey documented 4-foot high "grasses common to tide flats," likely including or dominated by *Schoenoplectus pungens*. Dotted line is approximate boundary of the Grays Harbor National Wildlife Refuge. Mile-long Grays Harbor City wharf had been built.

Figure 3-15. Hoquiam Hotel on 21 August 1898. Accumulated driftwood sits in marsh in the remaining delta of the river, the name of which means "hungry for wood." (University of Washington Libraries, Special Collections, Order Number WAS0456, Negative Number UW13183)

Figure 3-16. First engine to run on the new Northern Pacific railroad line connecting Hoquiam to Moclips in 1909. The rail was laid on fill at base of steep bluff west of Hoquiam. (University of Washington Libraries, Special Collections, Order Number WAS1060)

Figure 3-17. View of Hoquiam, Washington, from hillside to the north, c. 1910. Rennie Island is visible on far left side of photo, south of the mouth of the river. Smoke and steam obscure a portion of the island. (University of Washington Libraries, Special Collections, Order Number PPC151)

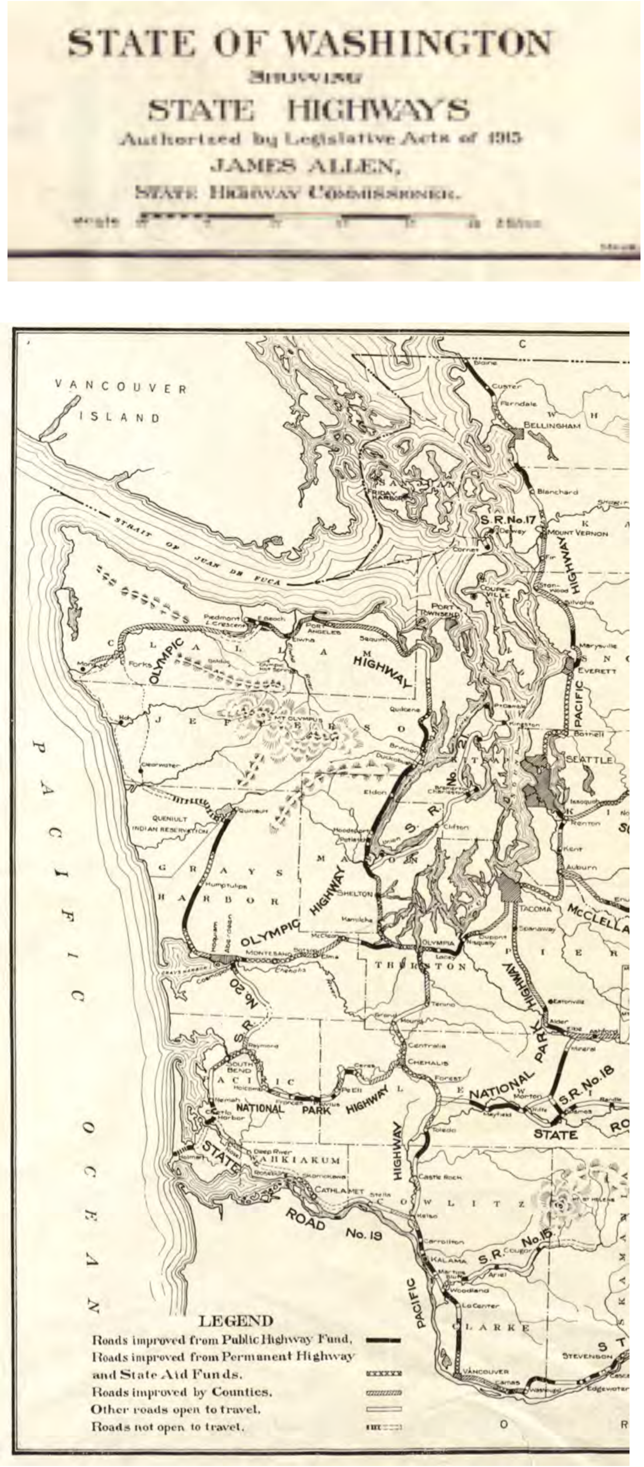


Figure 3-18. State of Washington map of State highways from 1915. The Hoquiam to Quinault (spelled Queniutl) portion of the Olympic Highway had been installed by this time and enabled some weavers to start driving to Bowerman Basin to collect sweetgrass.

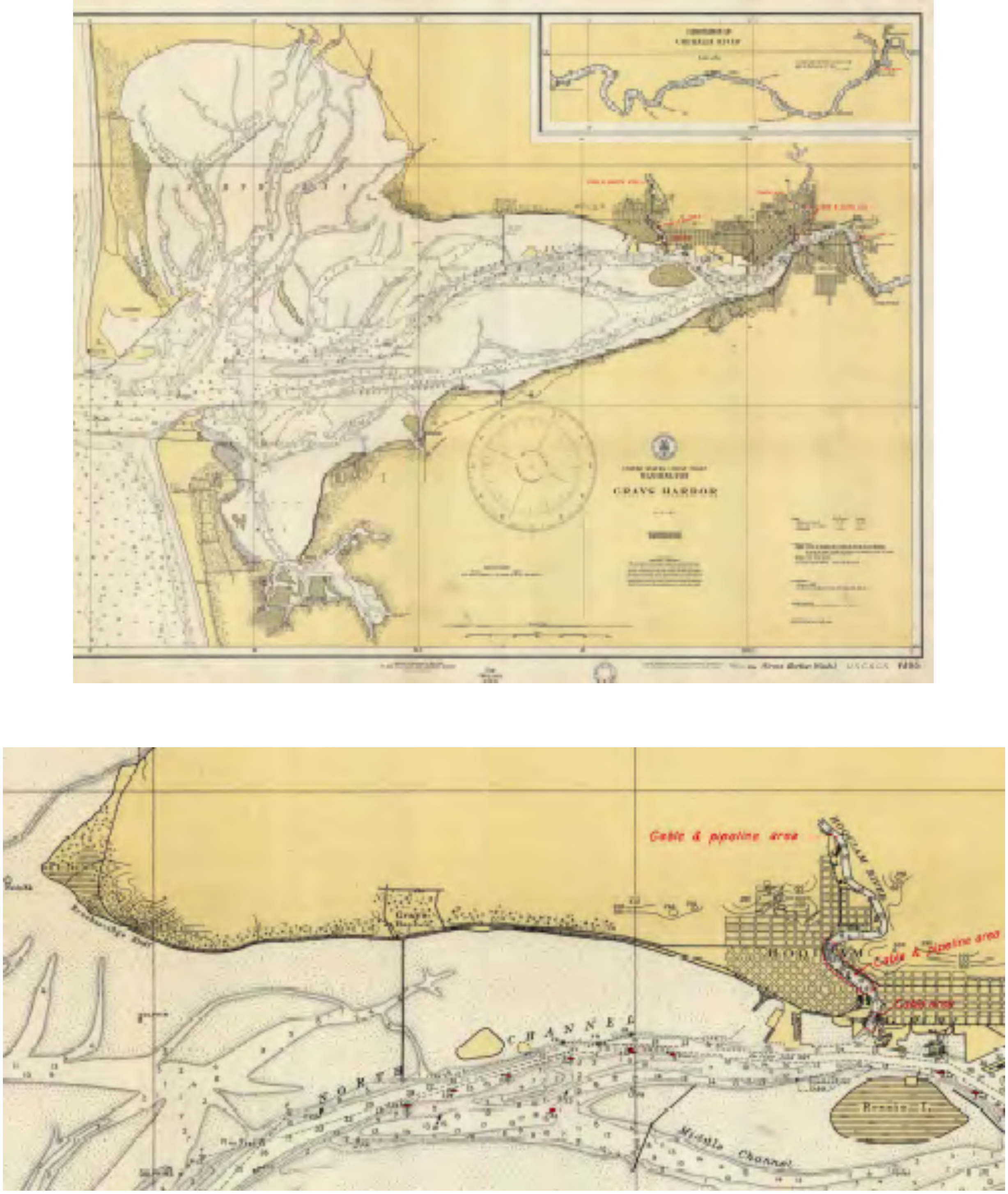


Figure 3-19. Nautical chart (#6195) of Grays Harbor, stamped 1928, and inset of north shore of inner bay. Note marsh on Rennie Island near the mouth of Hoquiam River, as well as at Point New. Note also mile-long Grays Harbor City wharf west of Hoquiam.

Figure 3-20. 1936 Corps of Engineers aerial photographs of confluence of Hoquiam River and Grays Harbor. Yellow dotted line is railroad constructed along original shoreline; red dotted line is approximate boundary of future Grays Harbor National Wildlife Refuge. Note fill on tide flats and apparent triangular area of vegetation in "corner" on the north shore east of the future wildlife refuge.

Figure 3-21. Expansion of Moon Island Airport by U. S. Army Air Corps as part of World War II West Coast defense. In foreground, note railroad trestle, which was used to transport materials from the north shore (just outside of the frame to the left) in the construction effort. Piling from this trestle remains in the wildlife refuge, and the eastern access point to the current gathering grounds is near these pilings where they reach the north shore. (Port of Grays Harbor, http://portofgraysharbor.com/about/history/index.php)

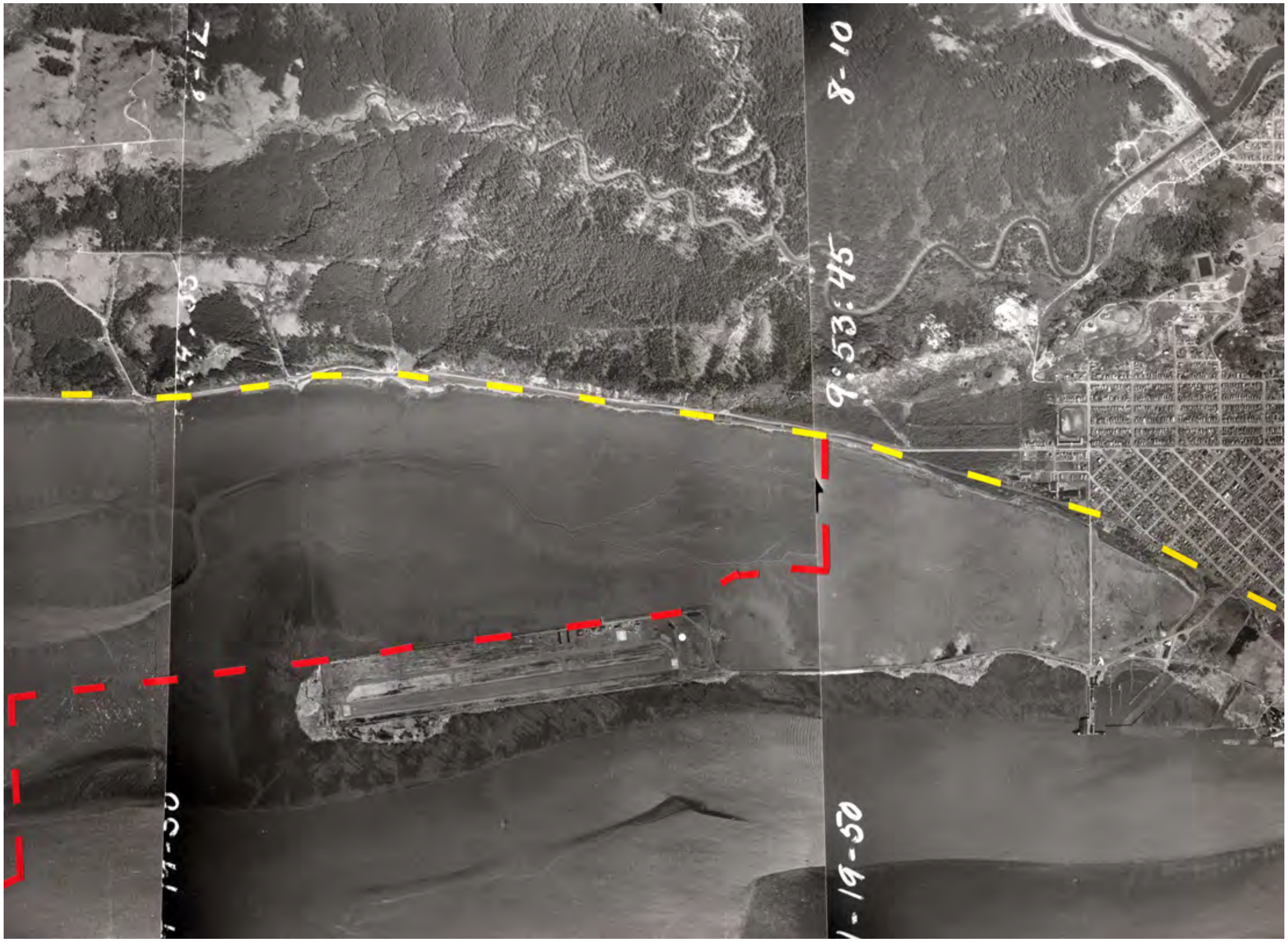
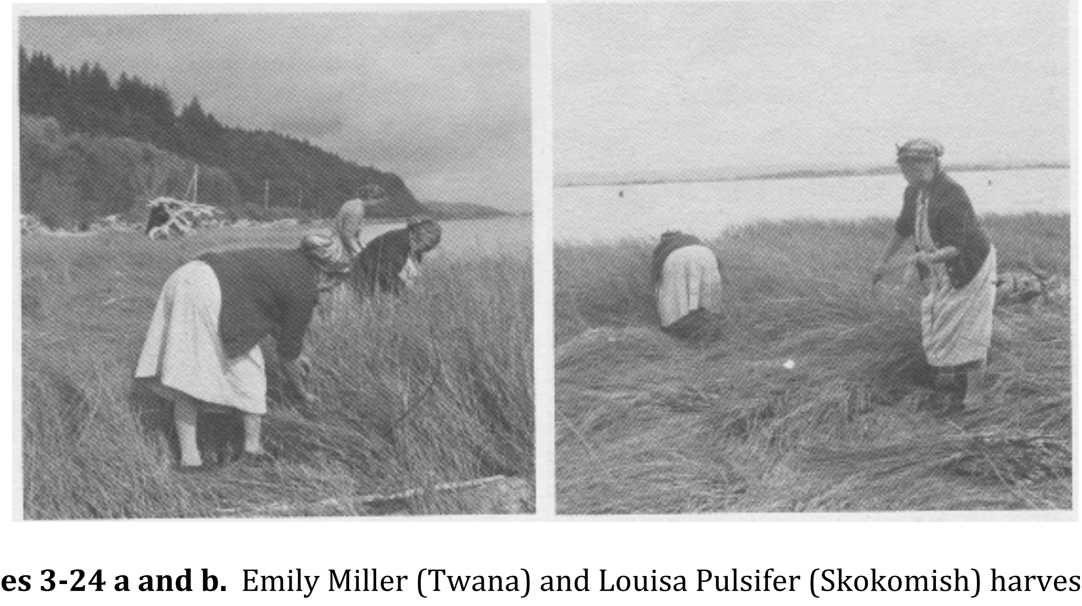


Figure 3-22. 1950 Corps of Engineers aerial photographs of confluence of Bowerman Basin. Yellow dotted line is railroad constructed along original shoreline; red dotted line is approximate boundary of Grays Harbor National Wildlife Refuge. Note construction of airport on tide flats and connection to Hoquiam via causeway.

Figure 3-23. Queets weavers bundling sweetgrass that they have gathered at Bowerman Basin sometime before 1977 (Peck and Peck 1977). (Charles and Elizabeth Peck Collection of Northwest Coast Indian Life, Washington State University Libraries, Pullman, Washington (20-3), as published in Shebitz and Crandell 2012:164)



Figures 3-24 a and b. Emily Miller (Twana) and Louisa Pulsifer (Skokomish) harvesting sweetgrass in Bowerman Basin in the 1970's. (Nordquist and Nordquist 1982)

Figure 3-25. 1974 Corps of Engineers aerial photographs of Bowerman Basin. Yellow dotted line is railroad constructed along original shoreline; red dotted line is approximate boundary of Grays Harbor National Wildlife Refuge. Note fill in inner basin between airport and north shore.

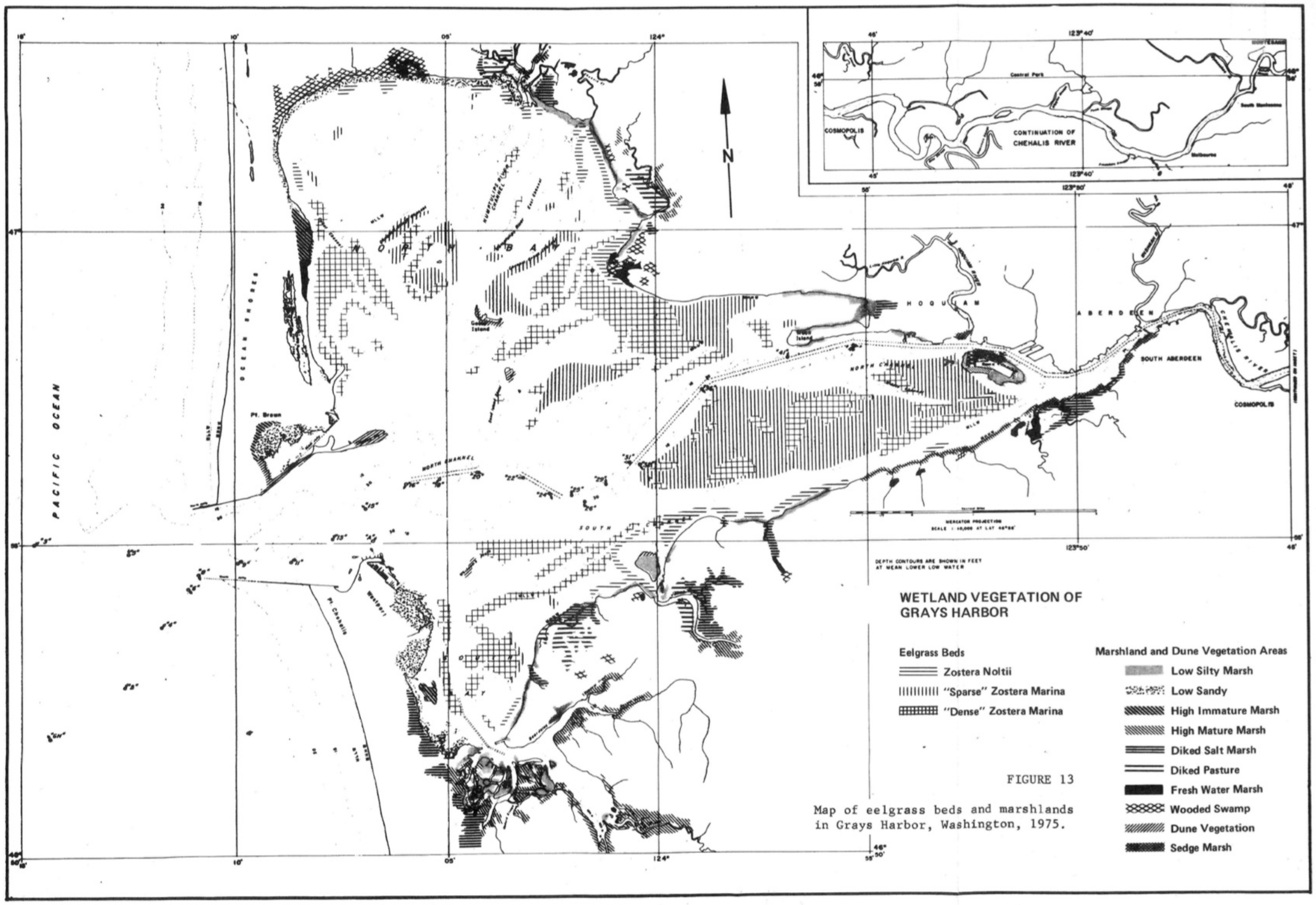


Figure 3-26. Wetland vegetation in Grays Harbor in 1975. Low silty marsh is shown along north shore of Bowerman Basin to just past the old railroad trestle to the airport. The same marsh type is shown between Humptulips River and Chenois Creek. Bowerman Basin was ground-truthed more thoroughly than the north bay shoreline (Smith et al. 1976).

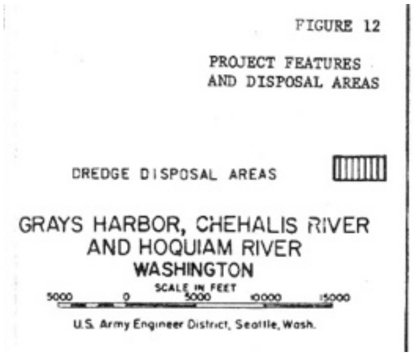


Figure 3-27. Deposition areas in Grays Harbor for sediment dredged from channels maintained for commercial vessels (Smith et al. 1976:57). Several sites are located at Bowerman Basin, including at the western end of the airport strip that is currently dominated by a large stand of *Schoenoplectus pungens*.

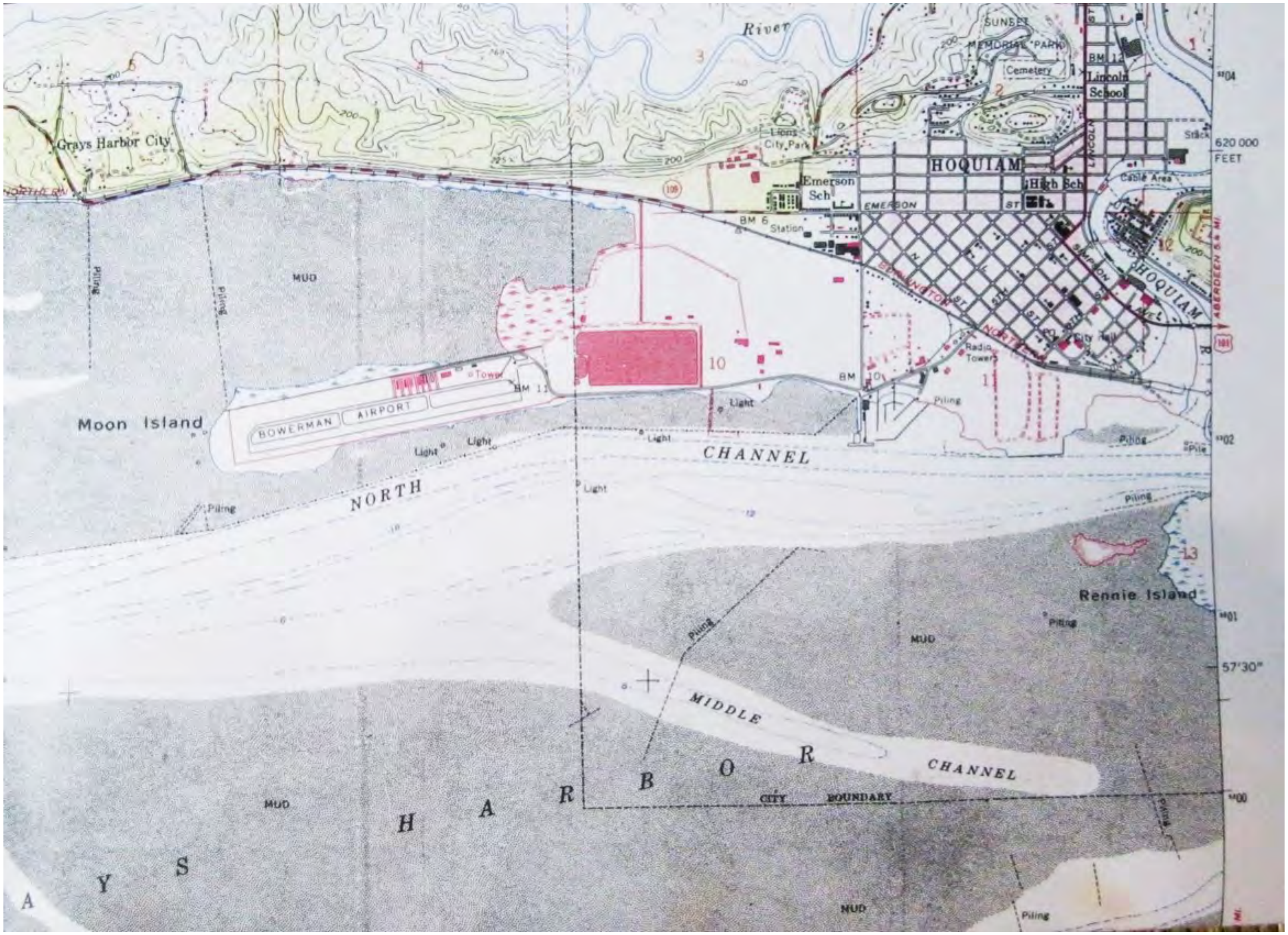


Figure 3-28. Portion of USGS topographic map (Hoquiam Quadrangle) published in 1957 and revised in 1983. Revisions are shown in red and include fill in Bowerman Basin and west of the vegetated area on Rennie Island.

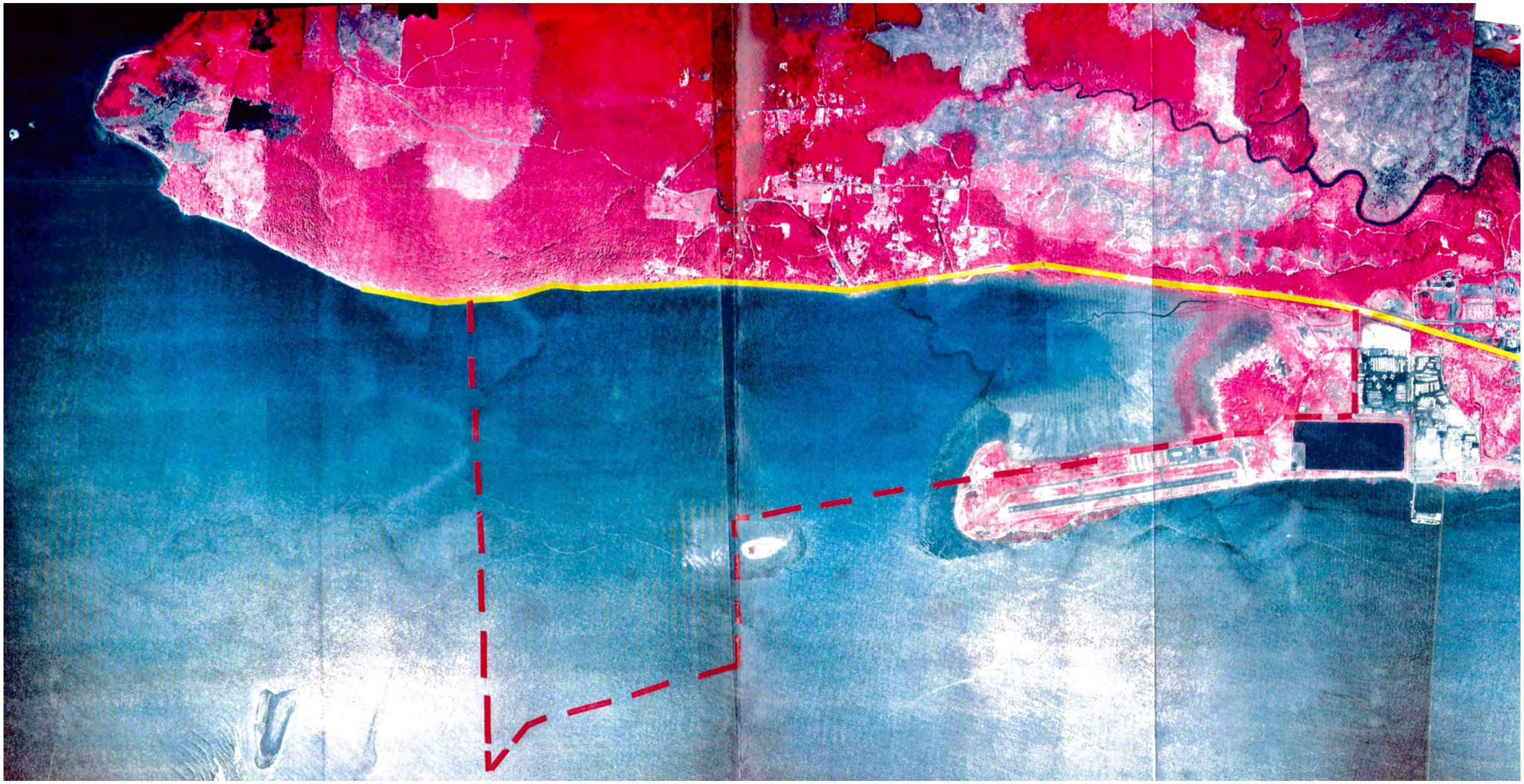
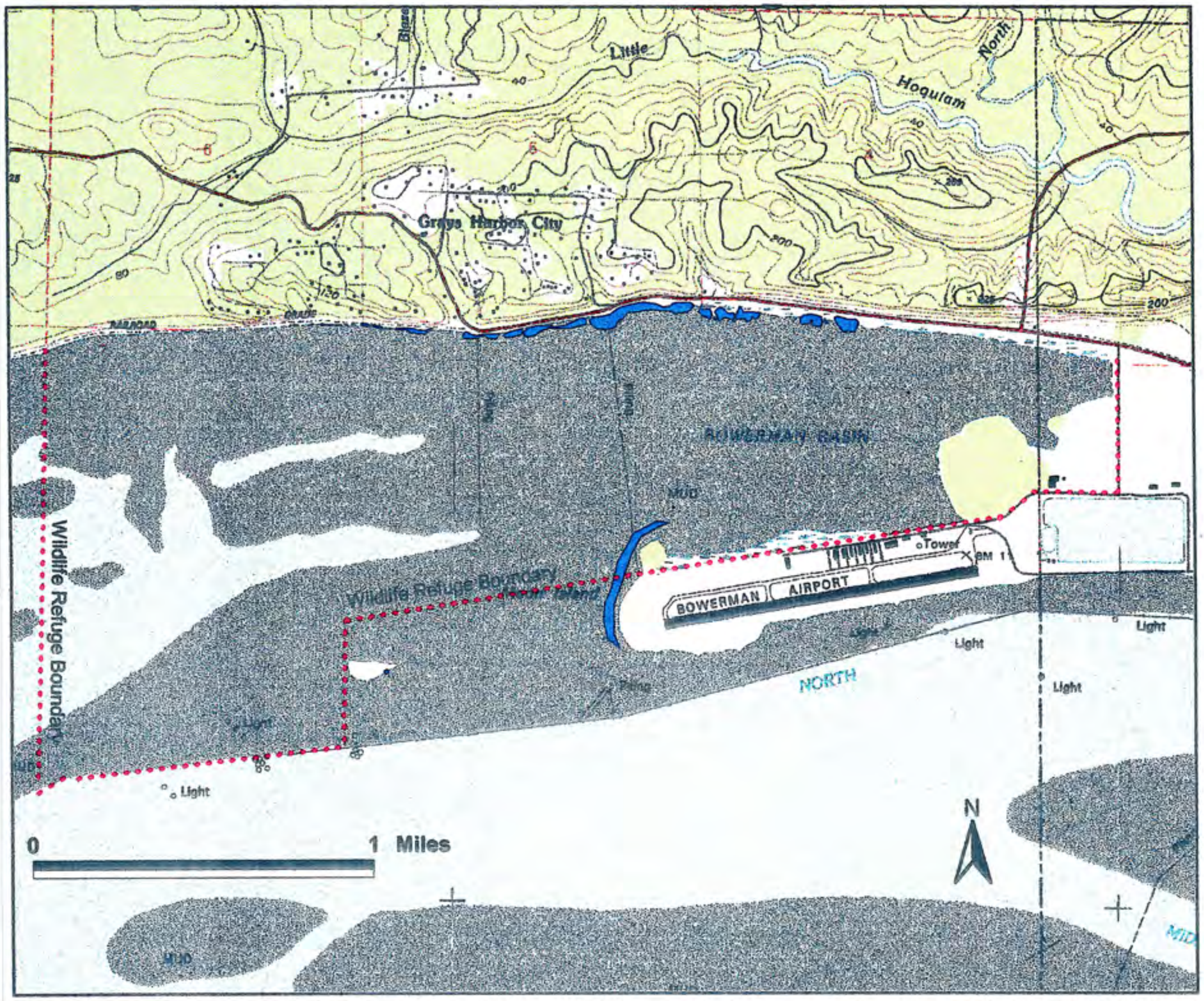


Figure 3-29. 1984 Corps of Engineers aerial photographs of Bowerman Basin. In color infrared photography, green vegetation appears red. Yellow dotted line is railroad constructed along original shoreline; red dotted line is approximate boundary of future national wildlife refuge. Sweetgrass was harvested during this decade along the north shore at both access points (i.e., old railroad trestle and old Grays Harbor City wharf). More vegetation is visible on the eastern half of the north shore.

Figure 3-30. 1990 Corps of Engineers aerial photographs of Bowerman Basin. In color infrared photography, green vegetation appears red. Yellow dotted line is railroad constructed along original shoreline; red dotted line is boundary of future national wildlife use.

Figure 3-31. Aerial photo of Grays Harbor National Wildlife Refuge, Hoquiam, Washington, taken by Washington State Department of Transportation on 28 August 1998. *Schoenoplectus pungens* grows in extensive stands along the north shore of Bowerman Basin and along the western end of the airport spit (a.k.a. south shore of Bowerman Basin).



*Schoenoplectus pungens (=Scirpus americanus) in blue shaded areas.
Mapped Aug/Sep 1998. Shoreline is approximate mean high water.

Hoquiam, WA USGS 7.5 Quad
1957 (rev. 1994)

Figure 3-32. *Schoenoplectus pungens* (blue polygons) in Bowerman Basin in Grays Harbor Wildlife Refuge, Hoquiam, Washington. Mapping was conducted in August and September 1998. (Crandell 1999)

Figure 3-33. Oblique aerial composite photo taken August 2016 of the relatively unaltered shoreline north of Chenois Creek, where *S. pungens* is dominant at lower elevations. (Photos: Washington State Department of Ecology, Shoreline Photo Viewer, https://fortress.wa.gov/ecy/shorephotoviewer/)

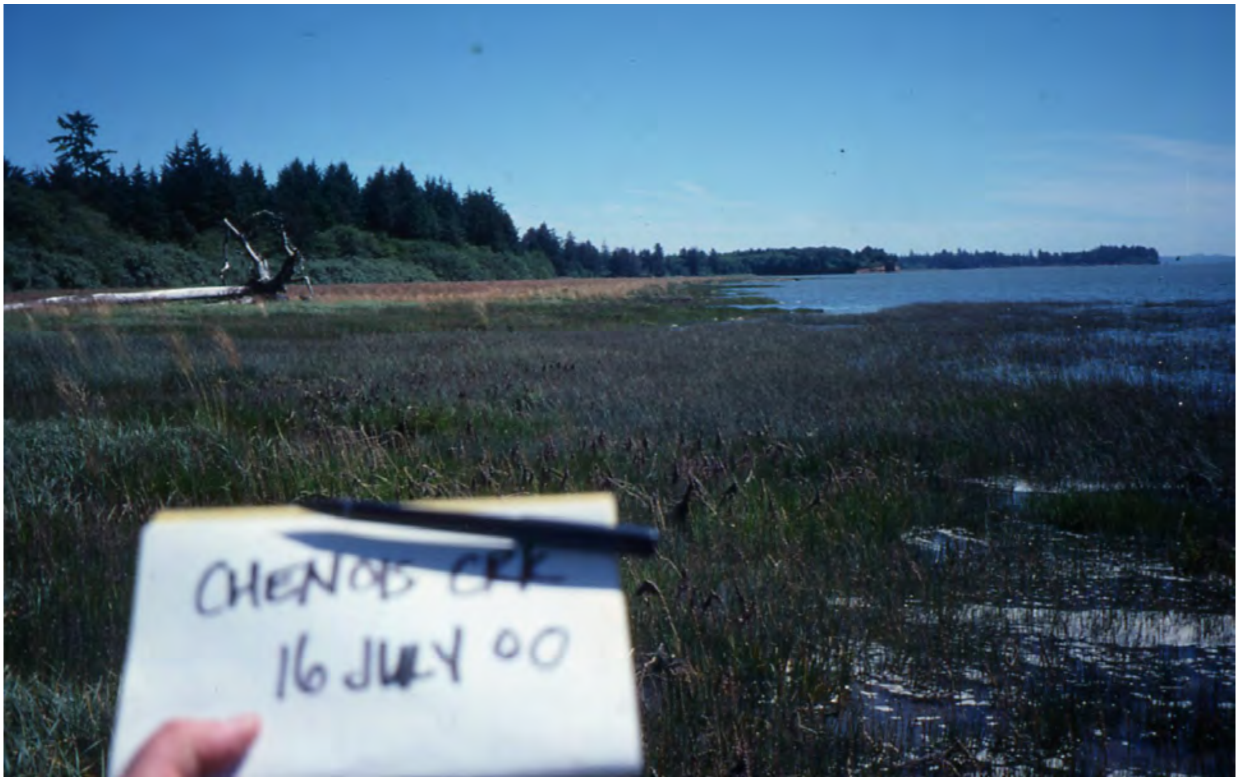
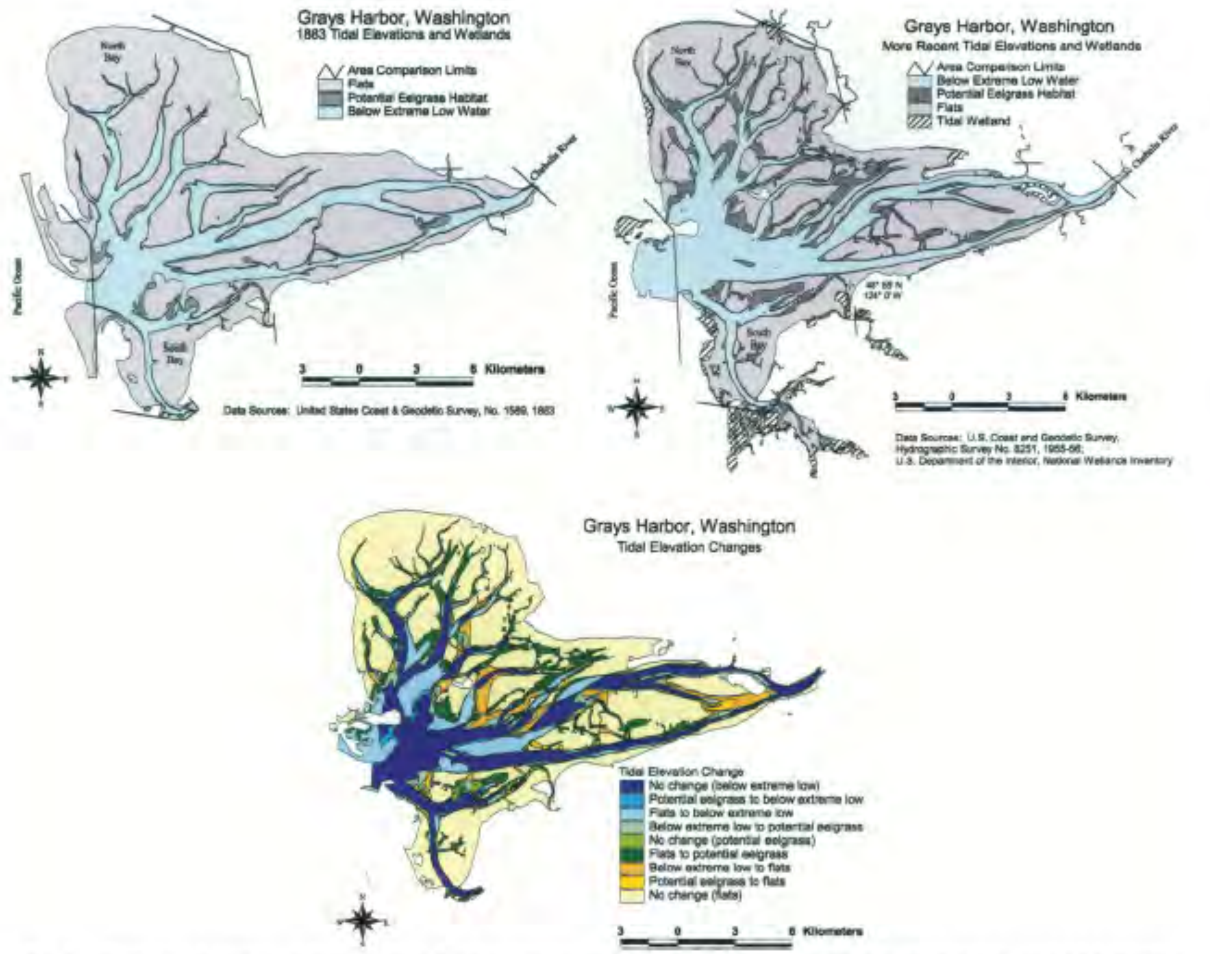


Figure 3-34. Schoenoplectus pungens stands between the Humptulips River and Chenois Creek on 16 July 2000. A major Native American village was located at Chenois Creek. This shoreline in Grays Harbor is relatively unaltered due to human activity. (Photo: Caren Crandell)



Grays Harbor, Washington
1883 Tidal Elevations and Wetlands

Data Sources: United States Coast & Geodetic Survey, No. 1589, 1883

Grays Harbor, Washington
More Recent Tidal Elevations and Wetlands

Data Sources: U.S. Coast and Geodetic Survey, Hydrographic Survey No. 8251, 1955-56; U.S. Department of the Interior, National Wetlands Inventory

Grays Harbor, Washington
Tidal Elevation Changes

Fig. 1. Historical depiction of Grays Harbor, Washington, present-day depiction of Grays Harbor, Washington, and tidal elevation change analysis results for Grays Harbor, Washington.

Figure 3-35. Historical analysis, using data from coastal surveys, hydrologic surveys, and wetland inventory, showed little change along shoreline in North Bay, in contrast to the Hoquiam area in the inner bay (Borde et al. 2003:1108).

Figure 3-36. Top map was creeted in conjuction with surveys conducted in the Humptulips/Chenois Creek area by the General Land Office in 1860. Such surveys paved the way for private ownership by European Americans. Bottom map shows the platting of the land as of 2005.

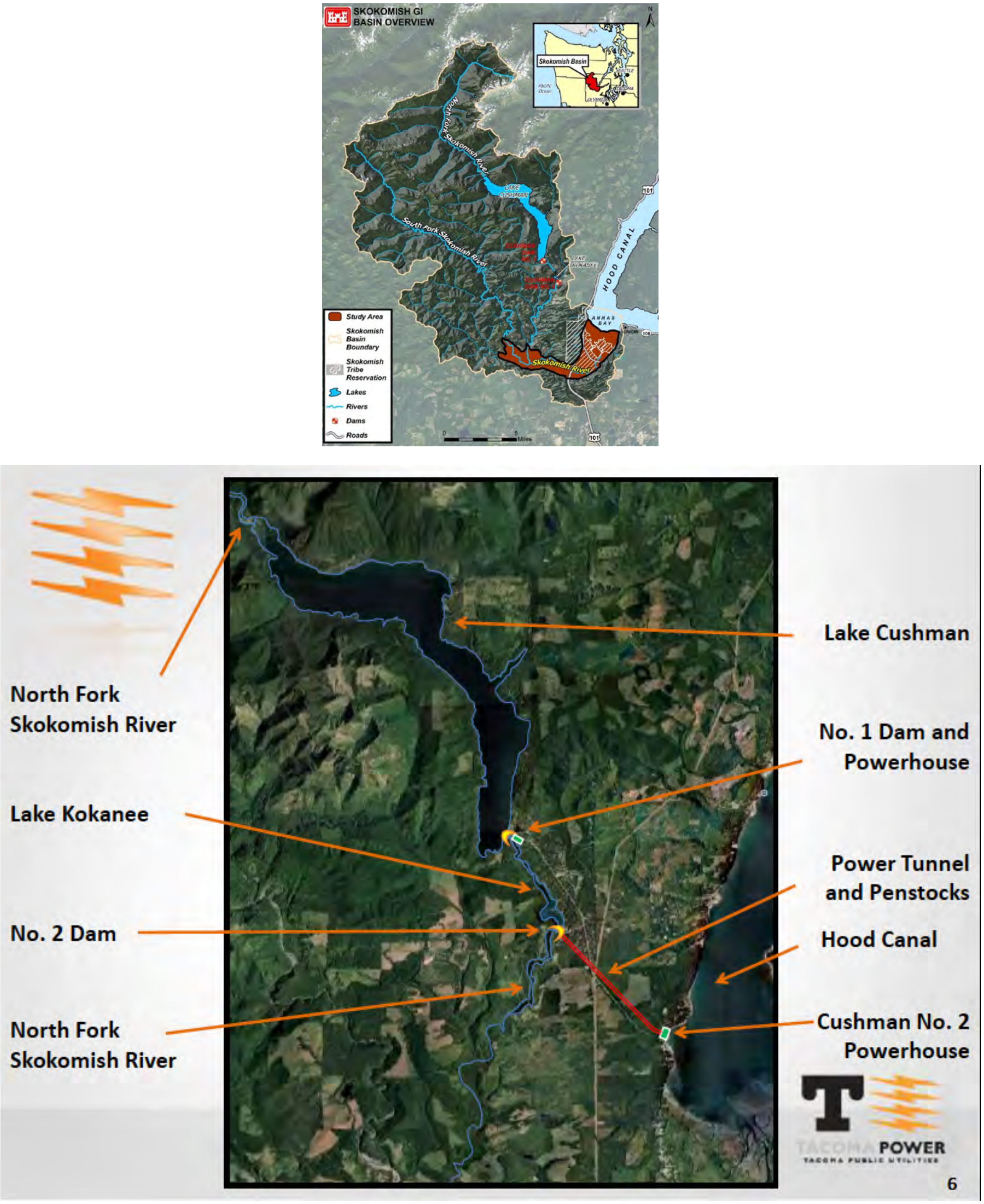


Figure 3-37. Top image is Skokomish River watershed (red indicates restoration areas; Gleason 2016: slide 3). Bottom image focuses on North Fork of the Skokomish River with components of hydropower system indicated in presentation by Tacoma Power (Fisher 2014: slide 6). Note especially the two dams and the diversion from the lower dam to Hood Canal, which bypasses the main stem and delta of the river.

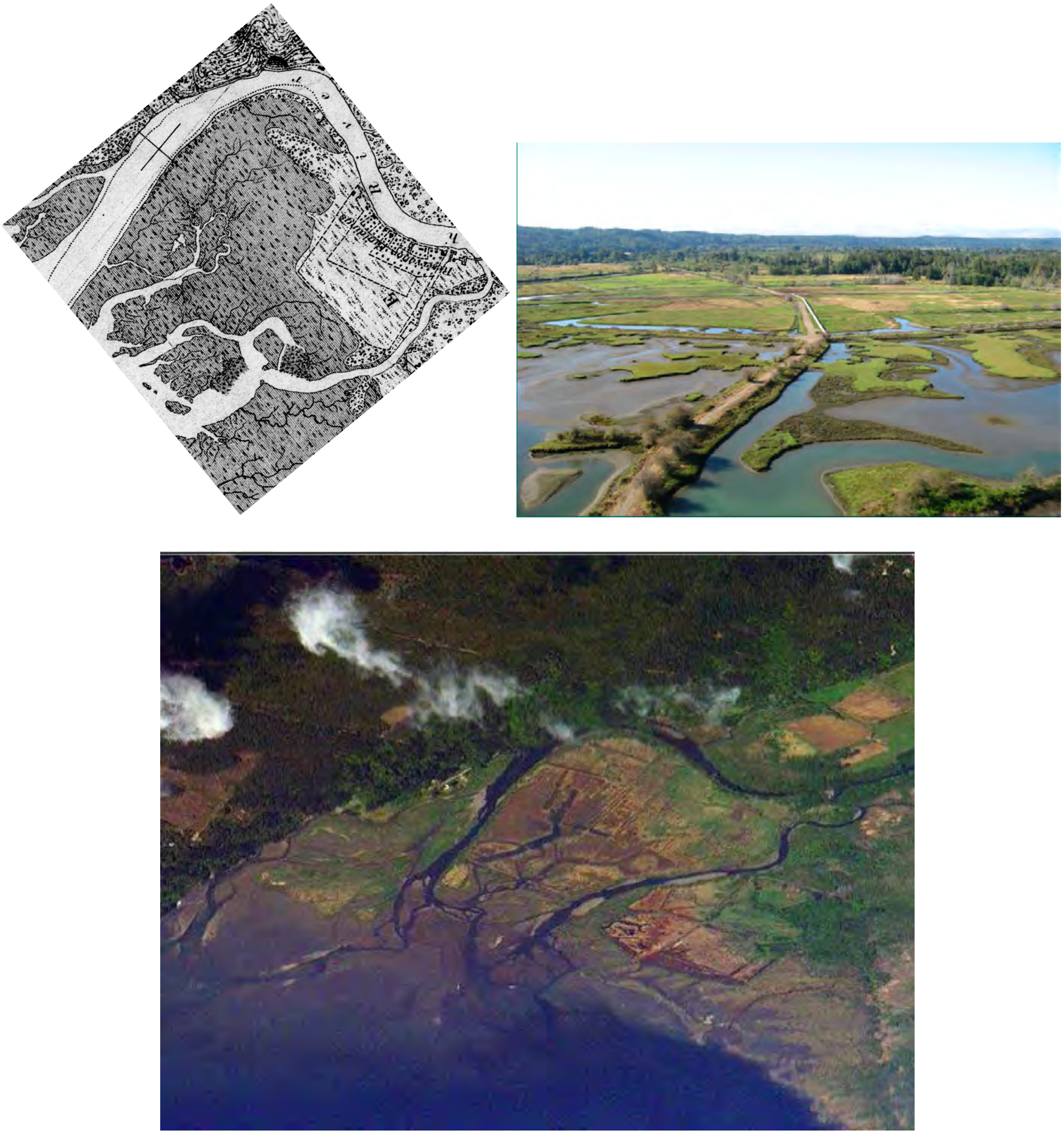


Figure 3-38. Skokomish River delta images showing the nature of the alterations: GLO survey map of Nalley Island shows extensive deltaic intertidal marshes (image is oriented to facilitate comparison to bottom image); upper right photo shows diking for agriculture (Dublanica 2010: slide 19), and the bottom photo shows Nalley Island and surrounding delta several years after restoration efforts have removed or breached dikes and reintroduced influence of tidal and river flooding (Gleason 2014: slide 16).

Figure 3-39. Legendary wetland plant botanist Fred Weinmann in *Schoenoplectus pungens* stand along Highway 105 east of Tokeland, where the North River flows into Willapa Bay, in mid-September 1999. Many of the up to 1-meter-tall stems in this stand were senescing at this time of year. Some *Spartina* was also seen at this site. Riprap lining side of roadbed is referred to as rocks in Tremblay's (1990) poem about harvesting sweetgrass here. (Photo: Ann Weinmann)

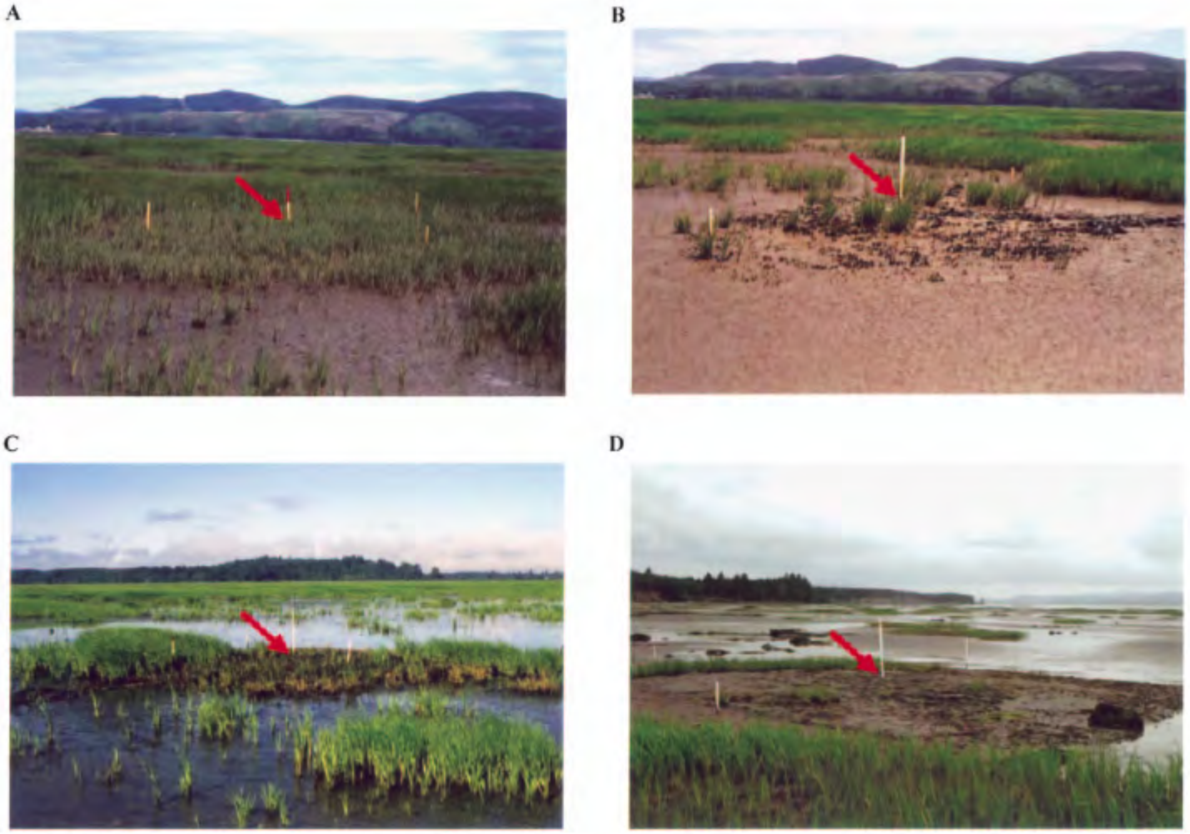


Figure 1. Treated clones (center denoted by red arrow) and adjacent untreated spartina: (A-C) mow, mow-spray and hand-spray at Lewis Unit, respectively, (D) mow-spray at Nemah.

Figure 3-40. Mechanical and chemical measures were applied to control invasive *Spartina alterniflora* in Willapa Bay. (Major et al. 2003:11)

Figure 3-41. Sweetgrass stands on the south side of Long Island in Willapa Bay in 2009. (Photos: Rick Pratt)