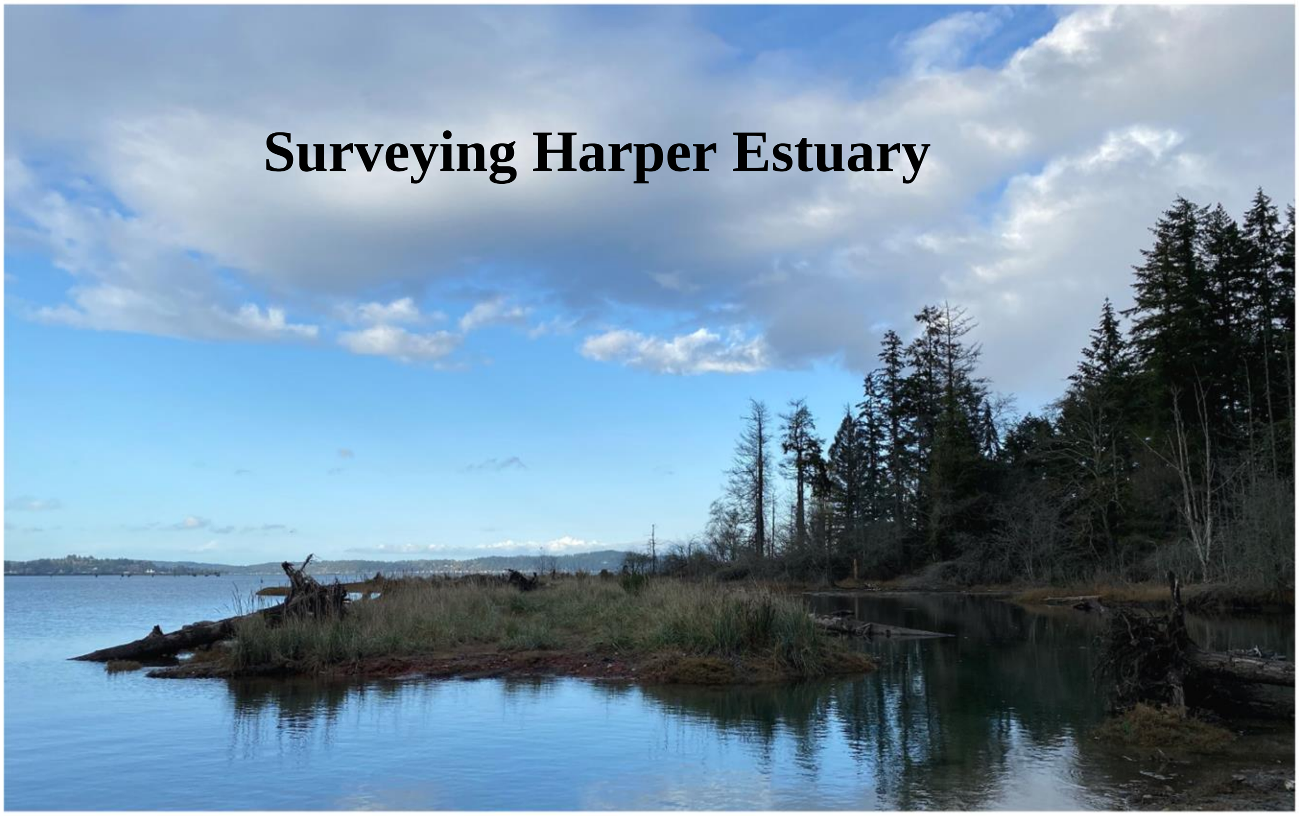
Surveying Harper Estuary



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Contents

Final Report: Surveying Harper Estuary

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Executive summary:

Vegetation and soil within estuarine ecosystems play an integral role in ecological processes within pocket estuaries. However, physical barriers, such as culverts within urban environments, disturb these processes by reducing hydrological inputs, sediment exchange, and habitat connectivity. The restoration of estuarine habitats by culvert removal and bridge replacement reconnects the aquatic corridor, however, the recovery of plant communities and soil substrate is not well understood. This project monitored a pre-restored site, Harper estuary, and compared that to three restored sites of variable ages (6-15 years) plus an undisturbed site on the Kitsap Peninsula in Western Washington. Plant community composition, soil organic carbon, organic matter, soil nutrients, water quality, and metals in sediments and plant tissue were assessed. Percent soil carbon was different among the pre-restoration and youngest (6 year) post-restoration site, demonstrating an initial decrease in carbon and organic matter during restoration. Nitrogen was deficient below the bridge of the newest restoration site, presumably linked to the lack of organic matter required for adequate cation exchange capacity and nutrient/plant exchange. Plant species diversity was higher at the intermediate (11 year) and oldest post-restoration sites (15 year), with a noted decline in Harper Estuary. Vegetation composition was primarily native species with few invasive plants. The development of a salinity gradient drives native plant assembly which increased in species diversity in the salt marshes of older sites. However, at Harper Estuary and the restored sites, vertical gradients maintained by deep channelization at the shoreline resulted in perched vegetation communities that are removed from the tidal influence. This resulted in a backwards gradient where freshwater and invasive species were allowed to colonize areas that were located along the nearshore, perched above the tidal flood plain. When comparing water quality throughout the estuaries, Harper Estuary had significantly higher summer temperatures, nitrates, dissolved solids, and salinity than the other restored or non-disturbed site. This was presumably due, in part by the lack of tidal flushing due to the culvert and subsequent morphology of the channels in the estuary resulting in higher metal concentration in plant tissue and higher salinity rates above the culvert. Harper estuary had a greater plant bioaccumulation of arsenic, cadmium, copper, lead, iron, manganese, and zinc. This is due to the higher rates of dissolved solids in the water column and higher levels of organic matter in the sediments when compared to the restored sites. It is noted that the restored sites were high in arsenic, cadmium, lead, silver, and zinc. The undisturbed reference site had much lower metals present in sediments with one exception, silver. Plants sequestered higher concentrations of arsenic, copper, iron, lead, manganese, and silver in root tissue when compared to stems and flower tissue. Further analysis will determine species with better accumulation rates to be used in future restoration sites.

Introduction:

Estuarine ecosystems spatially link freshwater and marine environments (Mitsch & Gosselink 2015). Hydrogeomorphology, vegetation, and soil are functionally interrelated and influence net primary productivity, sequestration of carbon, bioaccumulation of minerals and metals, and creation of wildlife habitat (Beaumont et al. 2007). Ecosystem services valuable to coastal wetlands include, storm abatement, temperature buffering, and water filtration. Despite the importance of these services, estuaries in the Pacific Northwest face increased disturbance as a result of commercial and private development (Lemly et al. 2000; Huppert et al. 2003). Loss of connectivity through implementation of physical barriers such as culverts, deeply channelize steams, diminish flood plains, and interrupts fish and wildlife (Bartz et al. 2006). Restoration by culvert removal and bridge replacement promotes energy movement and biophysical processes between biotic communities and abiotic factors, thereby improving stream morphology, water quality, tidal events, and migration routes (D'Agostini et al. 2015; Ellings et al. 2016). It is hypothesized that estuary restoration will result in the recovery of native vegetation communities and soil development, however, the length of time is not well understood (Suding et al. 2004).

The objective of this current project was to investigate the development of soil carbon, organic matter, plant nutrients, plant communities, heavy metals, and water quality within various urban estuary restoration sites in Western Washington, USA. Four sites were surveyed: 1) Harper Estuary, which represents a pre-restored culverted site, 2) six-year-old restored estuary, 3) 11-year-old restored estuary, and 4) 15-year-old restored estuary. In addition, water quality parameters and metal concentrations of estuary sediments and plant tissue was examined, and compared to a non-disturbed site. This study seeks to contribute additional information required to evaluate short-term, immediate development of pocket estuaries in various stages of recovery, and compare that to the culverted estuary located at Harper's. The results collected provides further evidence for estuary restoration by bridge replacement, document the threat of invasive species, and provide baseline data regarding soil development and threats of heavy metal deposition. Further, synthesis of multiple restoration sites will aid in management decisions for the restoration by bridge replacement at Harper Estuary.

Research Application of Parameters Monitored:

- Plant structure and community composition will detail the development of a salinity gradient, ability of native tidal plants to re-colonize, and document invasive species.
- Soil carbon and organic matter assess functional attributes of estuaries such as primary productivity and carbon cycling.
- Analysis of macro and micro-nutrients will assess biogeochemical cycling by detailing elemental deficiencies or heavy metal accumulation within sediments.
- Water quality data, which will reflect the flood channel dynamics, vegetation assembly, and sediment stability will be compared to the Washington State's water quality standards.

Material and Methods

Study Sites:

The five study sites are located on the Kitsap Peninsula in Washington State (Figure 1). The first site is the pre-site, Harper Estuary (47˚30'00.9"N 122˚30'58.4"W) in Port Orchard, Washington. This pre-restoration site contained one undersized culvert (60 cm in diameter) at the time of sampling. The second site, Carpenter Creek Estuary (47˚47'42.471"N 122˚30'26.7114"W), located in Kingston, Washington, was restored in 2013 after removal of a 3 m x 3 m box culvert on South Kingston Road and installation of a 27.4 m bridge that spans the entire channel width of Carpenter Creek and can withstand natural tidal inundation from Appletree Cove. The third site sampled was the nine-year-old site at the Beaver Creek Estuary (47˚34’12.1938”N 122˚33’7.2468”W), located in Manchester, Washington, at the head of Clam Bay and was restored in 2007. Restoration of Beaver Creek with the removal of the lower culvert and installation of a 7 m bottomless arch bridge at the head of Clam Bay were completed in 2007. The forth site was the 12-year-old site located at the Dogfish Creek Estuary (47˚44’48.3144”N 122˚39’7.3368” W), located in Poulsbo, Washington at the head of Liberty Bay. This site was restored in 2004 with the removal of a 1.5 m culvert, which was replaced with a 26.8 m bridge. A fifth site, Dewatto Estuary (47˚27’12.167”N 123˚02.939”W), was added to represent a non-disturbed site for comparison of water quality and metal concentration in sediments and plant tissue.

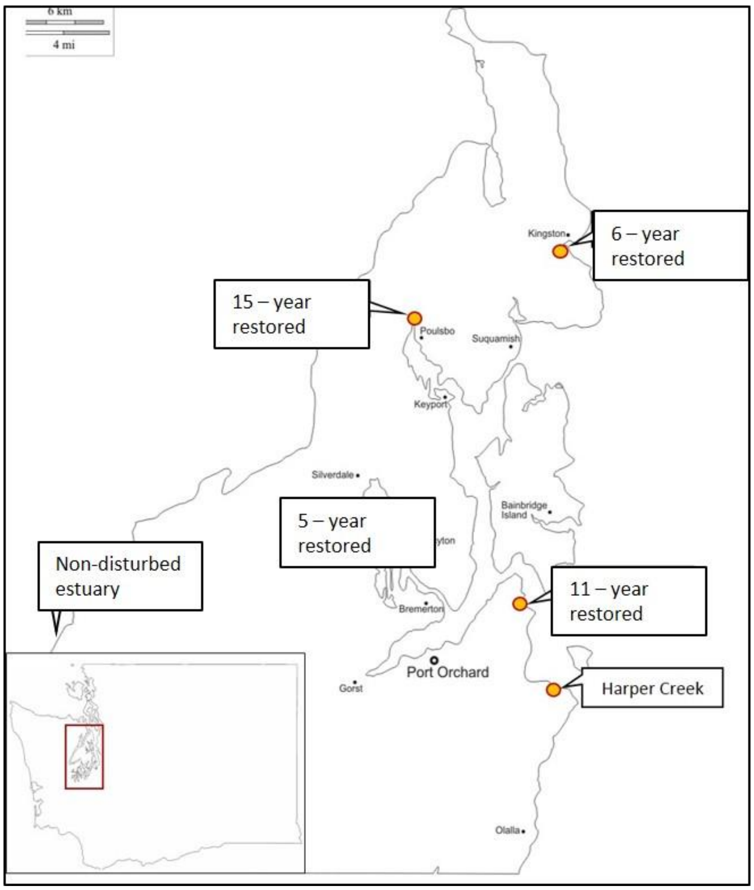

Figure 1. Map of study sites in Kitsap County, Washington State. Located on the Olympic Peninsula, sites within this study include Harper Estuary (pre-restoration), Carpenter Creek (6-Yr), Beaver Creek (11-Yr), and Dogfish Creek (15-Yr).

Vegetation Assessment:

Transects at each of the five estuary sites were placed parallel to the water along the lower bank edge, as described in the PacFish InFish Biological Opinion Monitoring Program (Archer et al. 2016). Three, 50-m line transects were placed above the culvert or bridge, and three 50-m transects were placed below (adjacent to marine water). Line-point intercept data was recorded along each meter of each transect where the nearest stem, leaf, or plant base intercepted the line. Each species was recorded to species using Hitchcock and Cronquist (1973) and MacKinnon and Pojar (1994). Vegetation height (cm) and percent cover were assessed using cover estimates in 18, 1 × 1 m quadrats, randomly selected on the transects.

Sample Preparation and Elemental Analysis:

At each of the four estuary sites, 25 cm x 25 cm sample of plant biomass and five, 3 cm soil cores (depth of 18 cm) were collected from the quadrats. All soil and plant biomass were returned to the WWU lab and dried at 45°C for one week. All soil was sieved to remove rocks greater than 1 cm in diameter. From each composite sample (soil or plant biomass), a 30 g sub-sample was mechanically ground into a fine powder using either a SPEX Mixer Mill and Wig-L-Bug Electric Mill, respectively. Dried, homogenized soil and vegetation samples were analyzed for total carbon and nitrogen using a Thermo Electron NC Soil Analyzer Flash EA 1112 Series (Thermo Electron Corporation, Milan, Italy). The remaining composite samples of both soil and vegetation biomass were digested (0.1 grams) in concentrated nitric acid at 170°C in Teflon® lined vessels in a CEM Mars 5 microwave digester and then diluted five times with water. Samples were analyzed for silver (Ag), arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn) using inductively coupled plasma-mass spectrometry (ICP-MS) at the Community Innovation Zone Laboratory at the University of Washington, Tacoma, WA.

Soil organic matter from the composited soil samples was determined using an optimized weight loss-on-ignition (WLOI) methodology specific to estuarine sediment (Wang and Wang 2011). Soil was dried overnight at 110°C to remove any absorbed water. Approximately two to three grams of soil was added to a ceramic crucible and the combined weight of the sample and crucible was recorded. The samples were then placed in a muffle furnace at 550°C for four hours. Crucibles were removed and cooled for 10 minutes before being weighed. Carbon content was determined by percent WLOI and was calculated by determining the difference of final soil weight after samples were heated for four hours, from the initial soil weight (Eq. 1).

$$\%\ \text{WLOI} = 100 \text{ x } \left(\frac{[(\text{Wdry soil weight (g)} - \text{Crucible wt (g)}) - (\text{W550(g)} - \text{Crucible wt (g)})]}{(\text{Wdry soil weight (g)} - \text{Crucible wt (g)})}\right)$$

Eq. 1: Percent Weight Loss-on-Ignition

Water Quality Parameters:

Water quality data were recorded during the summer from Harper Estuary and compared to the Washington State’s water quality standards among all restoration sites. Using an YSI field unit, parameters such as dissolved oxygen, pH, salinity, and temperature was collected. An additional probe recorded conductivity and total dissolved solids.

Statistical Analyses:

A multiple analysis of variance (MANOVA) was used followed by a two-way fixed-effects analysis of variance (ANOVA) to compare percent carbon, soil organic matter, macro and micronutrients, species richness, species abundance using the Shannon-Wiener (H'), number of invasive species, water quality parameters, and metal concentrations in both sediments and plant tissue occurrences at each site. The fixed effects were site (pre, 6-Yr, 11-Yr, and 15-Yr) and location (above and below) with an interaction term. Levene's test and Shapiro-Wilk's was used to assess how well data fit the assumption of homogeneity of variances and normally distributed populations, respectively. A log transformation was applied, when needed, prior to the ANOVA. A post-hoc pairwise comparison was used for sites and locations with significant ANOVA results (P-value < 0.05) using the "holm" P-adjustment method. When data could not be transformed to meet the assumptions of ANOVA, a Kruskal-Wallis non-parametric test was used. All statistical analyses were performed using R software (Version 3.3.0; R Core Team 2016; Vienna, Austria).

Results:

Percent Soil Carbon, Organic Matter, and Nutrients:

Cation exchange capacity (CEC) differed per site with higher levels associated with the oldest restoration sites and the and pre-site and lowest levels recorded in sediments associated with the 6-year-old sites, below the bridge ($F_{(3,16)} = 4.40$, $P = 0.002$). There was a significant interaction between site and location when soil carbon percentages were compared ($F_{(3,16)} = 3.68$, $P = 0.03$; Table 1). The newest restoration site (6-Yr) below the point of culvert restoration was significantly lower in soil carbon (0.9%) when compared across the other sites (2.2% - 7.5%). Pair-wise post-hoc tests indicate similarities between Harper Estuary (the pre-restoration site) and the oldest post-restoration site (15-Yr) with intermediate values observed from the 11-Yr plots. There were also significant differences in percent soil organic matter between sites ($F_{(3,16)} = 6.92$, $P = 0.003$). Similar with soil carbon, the newest site (6-Yr) below the location of culvert restoration was significantly lower in soil organic matter (2.8%) when compared to the other sites, including Harper Estuary (ranging 1.7-3.7%; Table 1). There was a significant interaction between site and location (above and below) when concentrations of nitrogen (N) were compared among the sites ($P = 0.02$). Similar to soil carbon and organic matter, individual two-way ANOVAs determined this was driven by a significant nitrogen decrease below the bridge at the 3rd year, newest site ($P<0.05$; Table 1). Harper Estuary and the oldest restoration site were similar to the reference estuary.

Table 1. Soil cation exchange capacity (CEC), percent soil carbon (%C), soil organic matter (%SOM), and total percent nitrogen (%N) from five estuary restoration sites in Kitsap County, Washington. Samples were pooled for analysis from two distinct locations (above and below; n=23) at each site: Harper Estuary as the pre-restoration (pre), six (6-Yr), 11 years (11-Yr), and 15 years (15-Yr) post-restoration. Means connected by the same letter do not differ according to Tukey's HSD (α=0.05).

	CEC (cmol/kg)	%C	%SOM	%N
Pre-site				
Above	12.5 ± 0.4ab	3.5 ± 1.0a	10.9 ± 2.5ab	0.2 ± 0.1a
Below	15.3 ± 3.4a	7.5 ± 2.9a	17.2 ± 6.2ab	0.5 ± 0.2 a
6-yr site				
Above	10.2 ± 0.5ab	2.4 ± 0.4ab	6.8 ± 1.2ab	0.2 ± 0.1 a
Below	2.1 ± 1.1b	0.9 ± 0.5c	2.8 ± 1.0c	0.03 ± 0.01b
11-yr site				
Above	9.2 ± 0.8ab	2.0 ± 0.3bc	5.8 ± 0.7ab	0.1 ± 0.01a
Below	8.5 ±3.4ab	2.2 ± 0.7b	6.8 ± 2.2ab	0.1 ± 0.1 a
15-yr site				
Above	16.6 ± 2.3a	2.6 ± 0.9ab	11.9 ± 2.6ab	0.2 ± 0.1a
Below	14.4 ± 3.0a	4.6 ± 1.1ab	7.1 ± 1.7ab	0.3 ± 0.1a
Reference Site				
Above	*NA*	5.0 ± 0.8a	13.9 ± 2.3ab	0.3 ± 0.1a

Superscript letters indicate homogenous subsets, as determined by Tukey's HSD.

Vegetation:

No differences existed when plant height, aboveground biomass, and species richness was compared among sites and locations. A significant difference between site was noted for plant species diversity by site ($F_{(3,16)} = 23.58$, $P < 0.001$; Table 2). Harper Estuary (pre-restoration site) was the only site with significant differences in plant species diversity between above vs. below location ($P<0.005$; Table 2). Additionally, the Shannon-Wiener (H') index of species diversity was significantly highest at the oldest post-restoration site (1.98 ±0.04), followed by the reference site. A trend toward a more diverse plant community assemblage can be seen over time. There were no significant difference when species richness was compared.

Table 2. Plant structure described as plant height, biomass, Shannon Weiner diversity, and species richness of four estuary restoration sites in Kitsap County, Washington. The five sites include Harper Estuary as the pre-restoration (pre), Dewatto Estuary as the reference site (Ref), six (6-Yr), 11 years (11-Yr), and 15 years (15-Yr) post-restoration. Two distinct locations at each site were measured (above and below culvert restoration; n=24). Of these, the 15-Yr site was significantly more diverse and had more species present than all other sites. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

	Plant height (cm)	Plant Biomass (g/m2)	Plant species Diversity	Species Richness
Pre-site				
Above	25.3± 2.0	56.3± 21.7	1.2 ± 0.1^{c}	6.3 ± 0.3
Below	41.2± 17.5	54.5± 15.6	1.9 ± 0.2^{ab}	11.3 ± 1.5
6-year site				
Above	20.1 ± 4.4	88.7± 32.6	1.3 ± 0.2^{c}	7.5 ± 0
Below	56.6± 8.3	79.3± 8.3	1.4 ± 0.1^{abc}	7.6 ± 0.3
11-yr site				
Above	39.9±6.0	104.1± 37.2	1.3 ± 0.04^{c}	8 ± 0.8
Below	39.7± 0.9	43.0± 27.9	1.4 ± 0.01^{bc}	7.6 ± 0.4
15-Yr site				
Above	33.5± 10.0	114.3± 23.8	2.0 ± 0.1^{ab}	10.2± 0.3
Below	25.0± 3.4	53.9± 21.4	2.7 ± 0.1^{a}	12.2± 1.2
Reference				
Above	21.2 ± 3.4	86.4± 12.4	1.7 ± 0.1^{abc}	9.0 ± 1.2
Below	25.5 ± 3.7	79.7± 9.2	1.7 ± 0.2^{abc}	8.0± 1.3

Summer vegetation surveys documented a total of 66 plant species (Table 3). The Chao estimated 73 (±9) species followed by the bootstrap method, which estimated a population size of 66 (±3). The native plant species abundant throughout all the sites included: pickleweed (*S. virginica*; 19.2%), colonial bentgrass (*Agrostis capillaris*; 11.8%), orache (*A. patula*; 9.5%), and gumweed (*Grindelia squarrosa*; 8.0%). Vegetation composition differed significantly by site and location ($F_{(3, 23)} = 6.67$, $P = 0.005$). Invasive species were relatively uncommon at each site and marginal evidence of a difference was observed in the interaction of site and location of the number of invasive occurrences in point-intercept data ($F_{(3,40)} = 2.52$, $P= 0.07$). Nine invasive plant species were documented: Himalayan blackberry (*Rubus armeniacus*; 1.3%), Scotchbroom (*Cytisus scoparius*;

0.5%), reed canary grass (*Phalaris* arundinacea; 0.5%), hairy cat's ear (*Hypochaeris* radicata; 0.1%), Canada thistle (*Cirsium* arvense; 0.1%), ox-eye daisy (*Leucanthemum vulgare*; <0.1%), common tansy (*Tanacetum vulgare*; <0.1%), field bindweed (*Convolvulus arvensis*; <0.1%), and Queen Anne's lace (*Daucus carota*; <0.1%).

Table 3. Complete species list of 66 species recorded along transects (n=24), including scientific name, common name, location (above and below), native status, and relative species abundance (%) for all transect measurements located at five estuary restoration sites in Kitsap County, Washington including: Harper Estuary as the pre-restoration (Pre) site, Dewatto estuary as the reference site (Ref), and three post restoration sites aged: six (6-Yr), 11 years (11-Yr), and 15 years (15-Yr) post-restoration. Species are listed by their functional group and native status (N =Native and naturalized; NX = Noxious).

Species name	Abbrev	Common Name	Site (Pre, 6, 11, and 15)		Native Status	Relative Abundance (%)
			Above	Below		
Forbs and vines		-	-	-	-	-
Achillea millefolium	*AcMi*	Yarrow	N/A	Pre	N	<0.01
Argentina egedii	*ArEg*	Pacific Silverweed	Ref, 15-Yr	Ref, 11-Yr	N	0.25
Cakile edentula	*CaEd*	American Sea Rocket	6-Yr	6-Yr	N	0.71
Atriplex patula	*ChAl*	Orache	All Sites	All Sites	N	8.6
Cirsium arvense	*CiAr*	Canadian Thistle	11-Yr	N/A	NX	0.13
Convolvulus arvensis	*CoAr*	Bindweed	N/A	15-Yr	NX	<0.01
Cuscuta pacifica	*CuPa*	Dodder	6-Yr	N/A	N	<0.01
Cytisus scoparius	*CySc*	Scotch Broom	11-Yr	6-Yr, 15-Yr	NX	0.46
Daucus carota	*DaCa*	Queen Anne's Lace	N/A	15-Yr	NX	<0.01
Equisetum hymale	*EqHy*	Scouring Rush	11-Yr	N/A	N	0.04
Galium aparine	*GaAp*	Sticky Weed	N/A	6-Yr	N	<0.01
Grindelia squarrosa	*GrSq*	Gumweed	All Sites	All Sites	N	7.2
Honkenya peploides	*HoPe*	Seabeach Sandwort	N/A	6-Yr	N	0.29
Hypochaeris radicata	*HyRa*	Hairy Cat's Ear	6-, 11-, 15-Yr	11-Yr, 15-Yr	NX	0.13
Jaumea carnosa	*JaCa*	Fleshy Jaumea	Pre, Ref	Pre, Ref, 15-Yr	N	8.1
Lathyrus odoratus	*LaOd*	Sweet Pea	N/A	Pre, 15-Yr	N	0.75
Leucanthemum vulgare	*LeVu*	Ox-Eye Daisy	N/A	11-Yr	NX	0.08
Lotus corniculatus	*LoCo*	Bird's-foot Trefoil	N/A	11-Yr	N	1.3
Montia linearis	*MoLi*	Montia	Pre, 15-Yr	N/A	N	0.33
Plantago lanceolata	*PlLa*	English Plantain	11-Yr	11-Yr, 15-Yr	N	0.25
Plantago major	*PlMa*	Round Leaf Plantain	11-Yr	11-Yr	N	0.08
Plantago maritima	*PlMa.1*	Sea Plantain	Ref, 6-, 15-Yr	Pre, Ref, 15-Yr	N	1.9
Polygonum aviculare	*PoAv*	Knotgrass	15-Yr	15-Yr	N	0.04
Polystichum munitum	*PoMu*	Sword Fern	11-Yr	N/A	N	0.04
Prunella vulgaris	*PrVu*	Self-Heal	N/A	11-Yr	N	<0.01
Ranunculus repens	*RaRe*	Creeping Buttercup	11-Yr	N/A	N	0.04
Rumex acetosa	*RuAc*	Sorrel	N/A	11-Yr	N	0.04
Rumex crispus	*RuCr*	Curly Dock	N/A	11-Yr	N	0.04

Sagina maxima	*SaMa*	Coastal Pearlwort	6-, 15-Yr	Ref	N	1.3
Salicornia virginica	*SaVi*	Pickleweed	All Sites	All Sites	N	21.4
Spergularia canadensis	*SpCa*	Sand Spurry	Ref, 15-Yr	Pre, Ref, 6-Yr	N	2.5
Symphyotrichum subspicatum	*SySu*	Douglas Aster	15-Yr	N/A	N	0.17
Tanacetum vulgare	*TaVu*	Tansy	11-Yr	N/A	NX	<0.01
Trifolium wormskioldii	*TrWo*	Red Clover	11-Yr	15-Yr	N	0.38
Triglochin maritima	*TrMa*	Seaside Arrowgrass	Ref, 6-, 15-Yr	Pre, Ref, 6-Yr	N	1.6
Graminoids		-	-		-	-
Agrostis capillaris	*AgCa*	Colonial Bentgrass	All Sites	All Sites	N	10.4
Agrostis exarata	*AgEx*	Spike Bent Grass	15-Yr	N/A	N	0.04
Calamagrostis canadensis	*CaCa*	Blue Joint Grass	15-Yr	N/A	N	0.25
Deschampsia cespitosa	*DeCe*	Tufted Hair Grass	Pre	N/A	N	<0.01
Distichlis spicata	*DiSp*	Saltgrass	Pre, Ref, 6-, 15-Yr	Pre, Ref, 15-Yr	N	9.8
Elymus glaucus	*ElGl*	Blue Wild Rye	N/A	Pre, 15-Yr	N	0.29
Elymus mollis	*ElMo*	Dune grass	N/A	Pre, 6-Yr	N	3.6
Elymus repens	*ElRe*	Quack Grass	All Sites	All Sites	N	1.1
Holcus lanatus	*HoLa*	Velvet Grass	11-, 15-Yr	11-Yr	N	0.21
Hordeum brachyantherum	*HoBr*	Meadow Barley	6-, 15-Yr	Pre, Ref, 6-Yr	N	4.4
Lysimachia maritima	*LyMa*	Sea Milkwort	Ref	NA	N	1.4
Phalaris arundinacea	*PhAr*	Reed Canary Grass	11-, 15-Yr	11-, 15-Yr	NX	0.46
Sedges and Rushes		-	-		-	-
Carex lyngbyei	*CaLy*	Lyngby Sedge	Pre, Ref, 6-, 15-Yr	Ref	N	2.1
Eleocharis palustris	*ElPa*	Spike Rush	11-Yr	N/A	N	0.13
Juncus effusus	*JuEf*	Common Rush	11-Yr	11-, 15-Yr	N	0.33
Juncus gerardii	*JuGe*	Saltmeadow Rush	Pre, Ref	Pre, Ref, 15-Yr	N	2.0
Woody plants		-	-		-	-
Acer macrophyllum	*AcMa*	Big Leaf Maple	11-Yr	Pre, 11-Yr	N	0.58
Alnus rubra	*AlRu*	Red Alder	11-Yr	11-Yr	N	0.58
Oemleria cerasiformis	*OeCe*	Oso Berry	N/A	Pre	N	0.67
Pinus contorta	*PiCo*	Shore Pine	N/A	15-Yr	N	0.63
Pseudotsuga menziesii	*PsMe*	Douglas Fir	N/A	Pre	N	0.21
Robinia pseudoacacia	*RoPs*	Black Locust	N/A	11-Yr	N	0.42
Rosa nutkana	*RoNu*	Nootka Rose	Pre	Pre, 11-Yr	N	0.63
Rubus armeniacus	*RuAr*	Himalayan Blackberry	Pre, 11-, 15-Yr	Pre, 11-, 15-Yr	NX	1.1
Rubus ursinus	*RuUr*	Trailing Blackberry	N/A	11-Yr	N	0.42
Salix sitchensis	*SaSi*	Sitka Willow	11-Yr	N/A	N	0.17
Salix hookeriana	*SaHo*	Hooker Willow	N/A	11-Yr	N	1.08

Symphoricarpos albus	*SyAl*	Snowberry	N/A	Pre, 9, 15-Yr	N	0.08
Tsuga heterophylla	*TsHe*	Western Hemlock	N/A	11-Yr	N	0.04
Other						
Bare Ground	*BaGr*	-	All Sites	All Sites	-	5.3
Large Woody Debris	*LWD*	-	All Sites	All Sites	-	1.17

Water Quality:

When comparing estuaries, Harper Estuary had significantly higher summer temperatures, nitrates, dissolved solids, and salinity than the other restored or non-disturbed site ($P < 0.05$; Figures 2 and 3). Nitrates at all sites were < the 10 mg/L recommended limit. Harper estuary had a greater plant bioaccumulation of arsenic, cadmium, copper, lead, iron, manganese, and zinc (all $P < 0.001$; Figures 4-11). It is noted that the restored sites were high in arsenic, cadmium, and zinc. The most recently restored site had the highest concentrations of lead and silver in sediments (Figures 7 and 10). The undisturbed reference site had much lower metals present in sediments with one exception, silver (Figure 11). Plants sequestered higher concentrations of arsenic, copper, iron, lead, manganese, and silver in root tissue when compared to stems and flower tissue ($P < 0.05$; Figure 12).

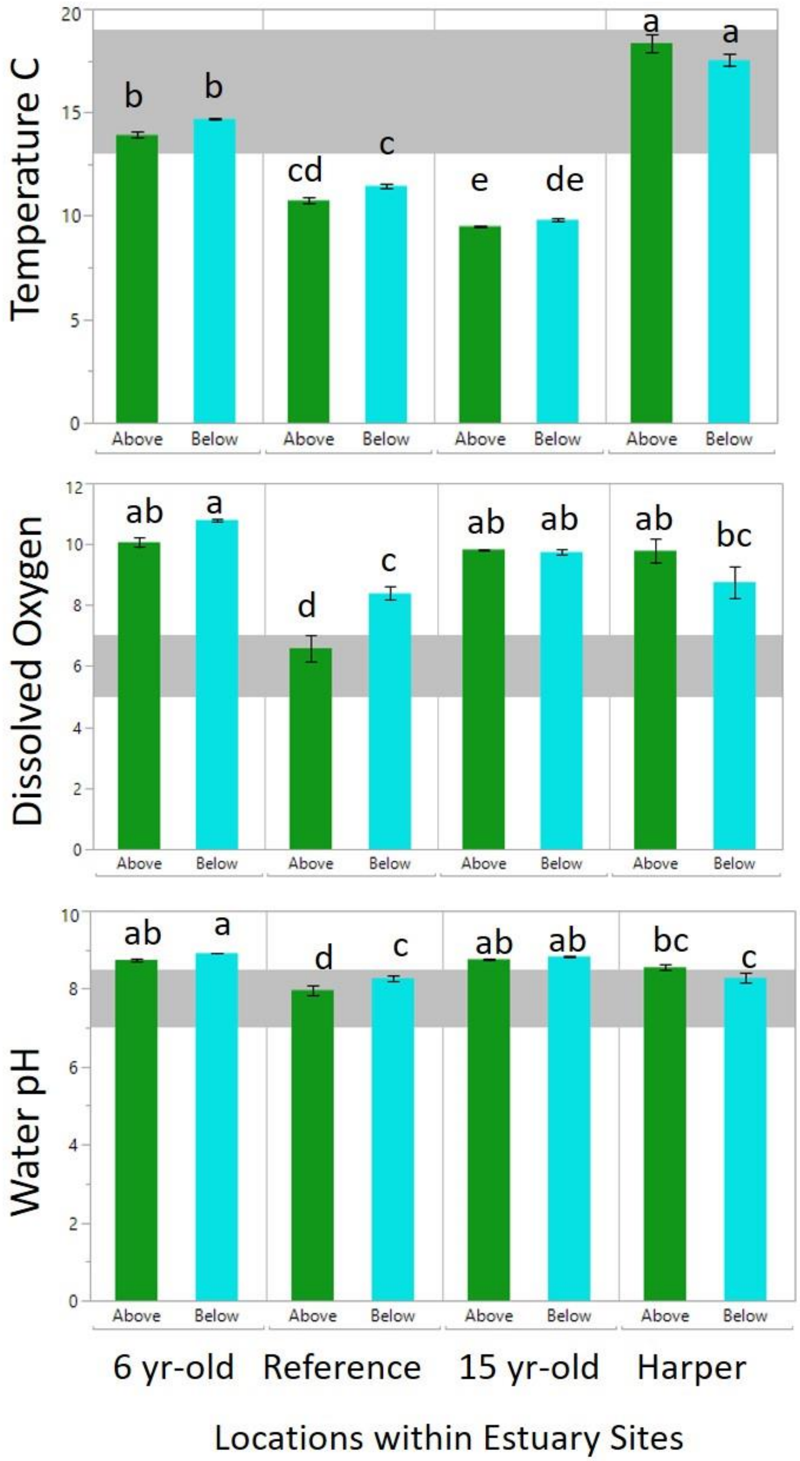

Figure 2: Bar graphs illustrating differences in water quality parameters among site and location where green bars represent sites above the bridge or culvert (green) compared to sites below (marine side; light blue bars). Horizontal gray bars indicate acceptable water quality ranges. When comparing estuaries, Harper Estuary had significantly higher summer temperatures that the other restored or non-disturbed site (P=0.001). Slight differences also existed when DO and pH were compared ((P=0.002 and P=0.001, respectively) with lower measurements within the non-disturbed sites. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

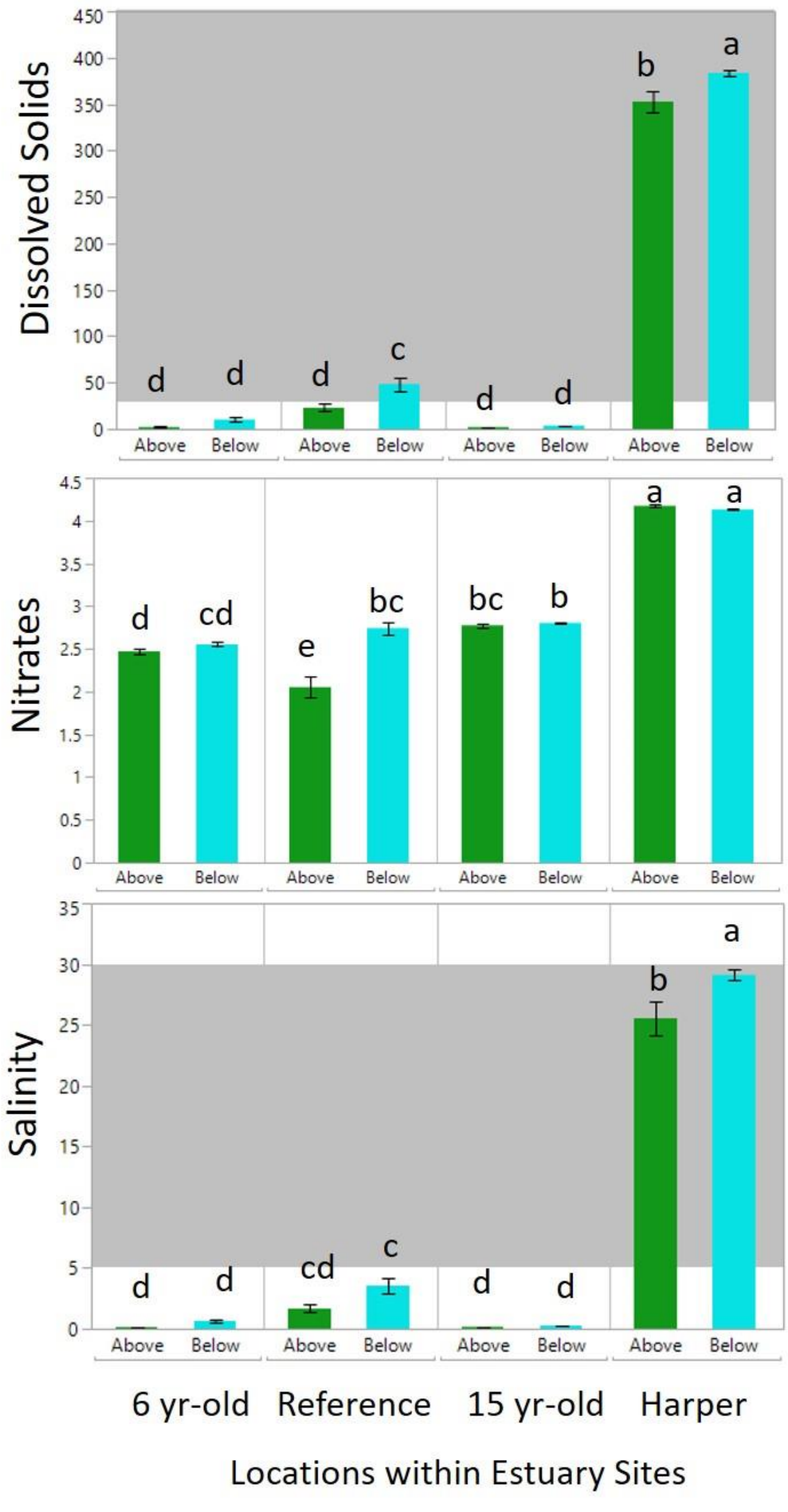

Figure 3: Bar graphs illustrating differences in water quality parameters among site and location where green bars represent sites above the bridge or culvert (green) compared to sites below (marine side; light blue bars). Horizontal gray bars indicate acceptable water quality ranges. When comparing estuaries, Harper Estuary had significantly higher dissolved solids, nitrates, and salinity summer temperatures that the other restored or non-disturbed site (all P<0.001). Please note that the nitrates at all sites were < the 10 mg/L recommended limit. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

Concentrations of Metals in Sediments and Soils:

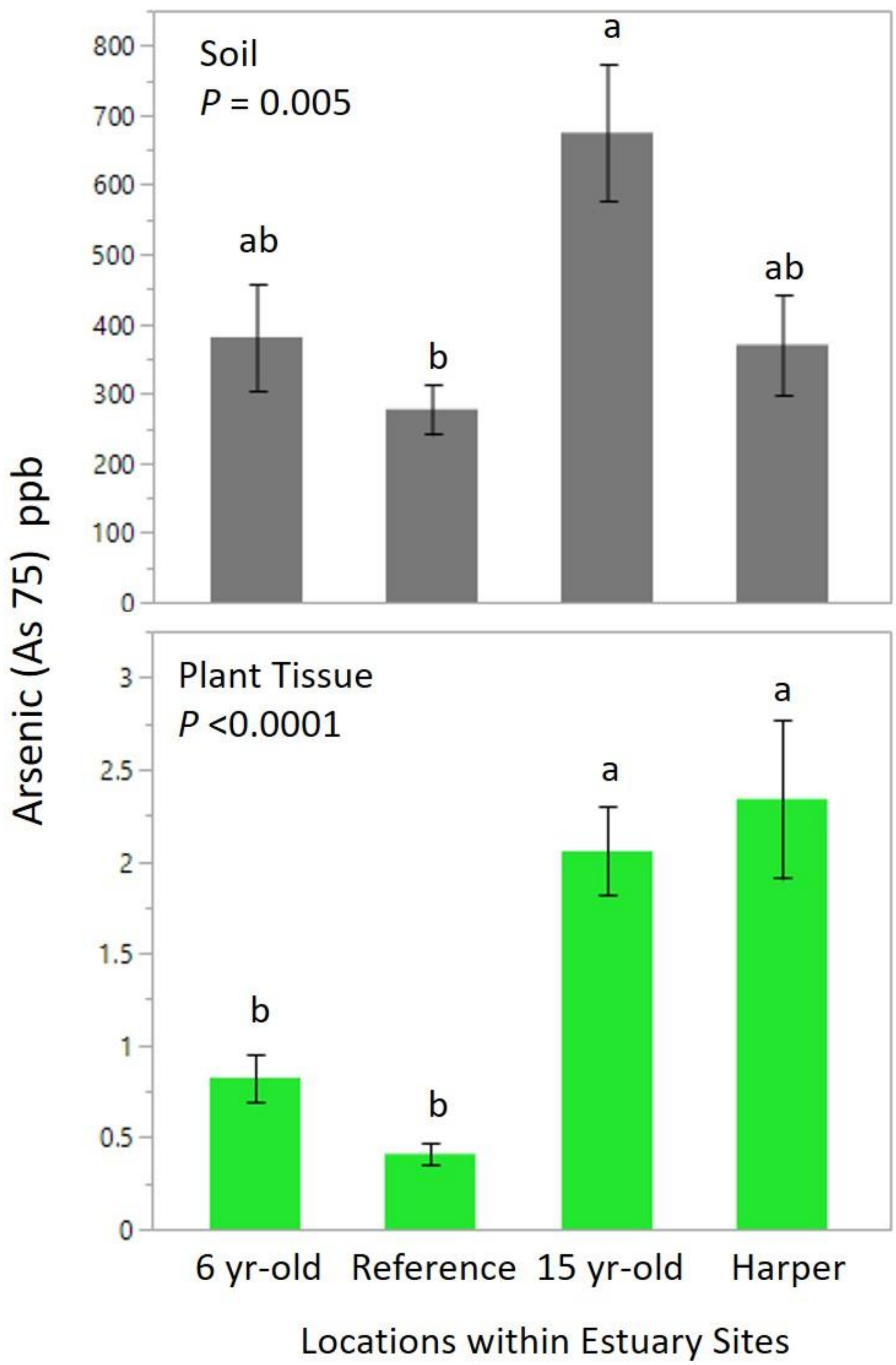

Figure 4: Concentration of arsenic measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in harper and the 15-year old restoration site. However, greater arsenic concentrations were observed in sediments in the six-year-old restoration site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

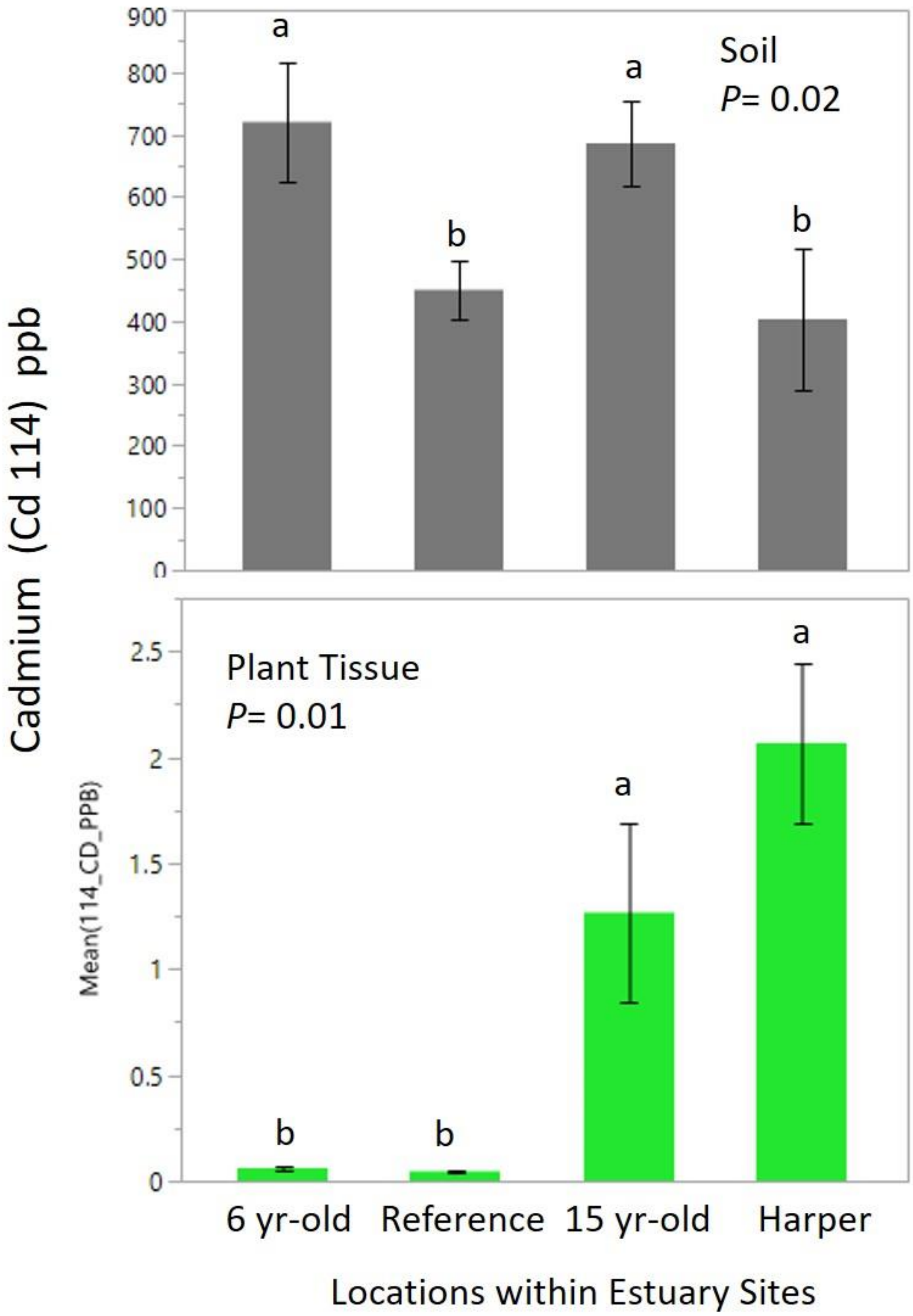

Figure 5: Concentration of cadmium measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in Harper and the 15-year old restoration site. However, greater cadmium concentrations were observed in sediments in the six-year-old and 15-year-old restoration site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

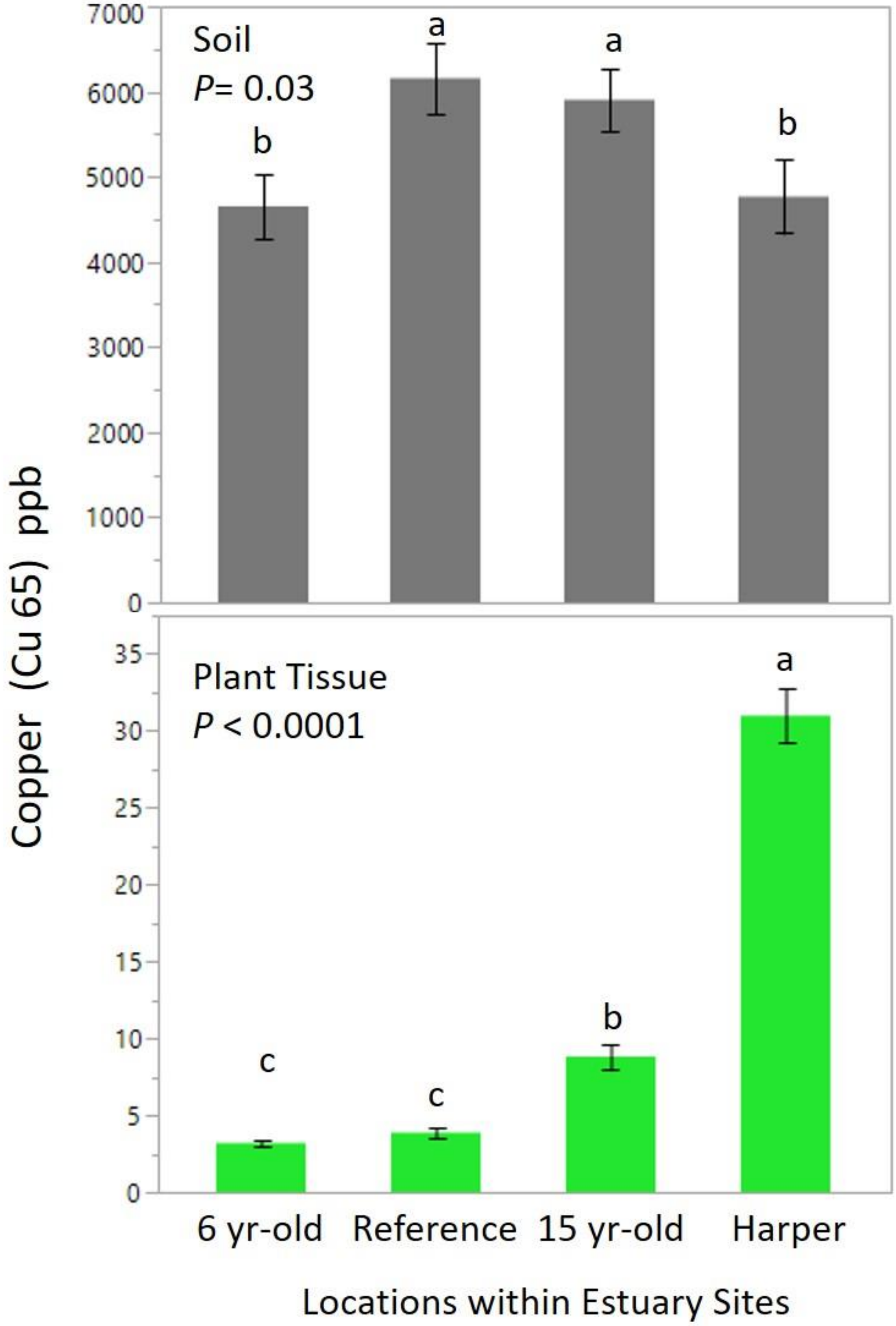

Figure 6: Concentration of copper measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in Harper Estuary site. However, greater copper concentrations were observed in sediments in the reference and 15-year-old restoration site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

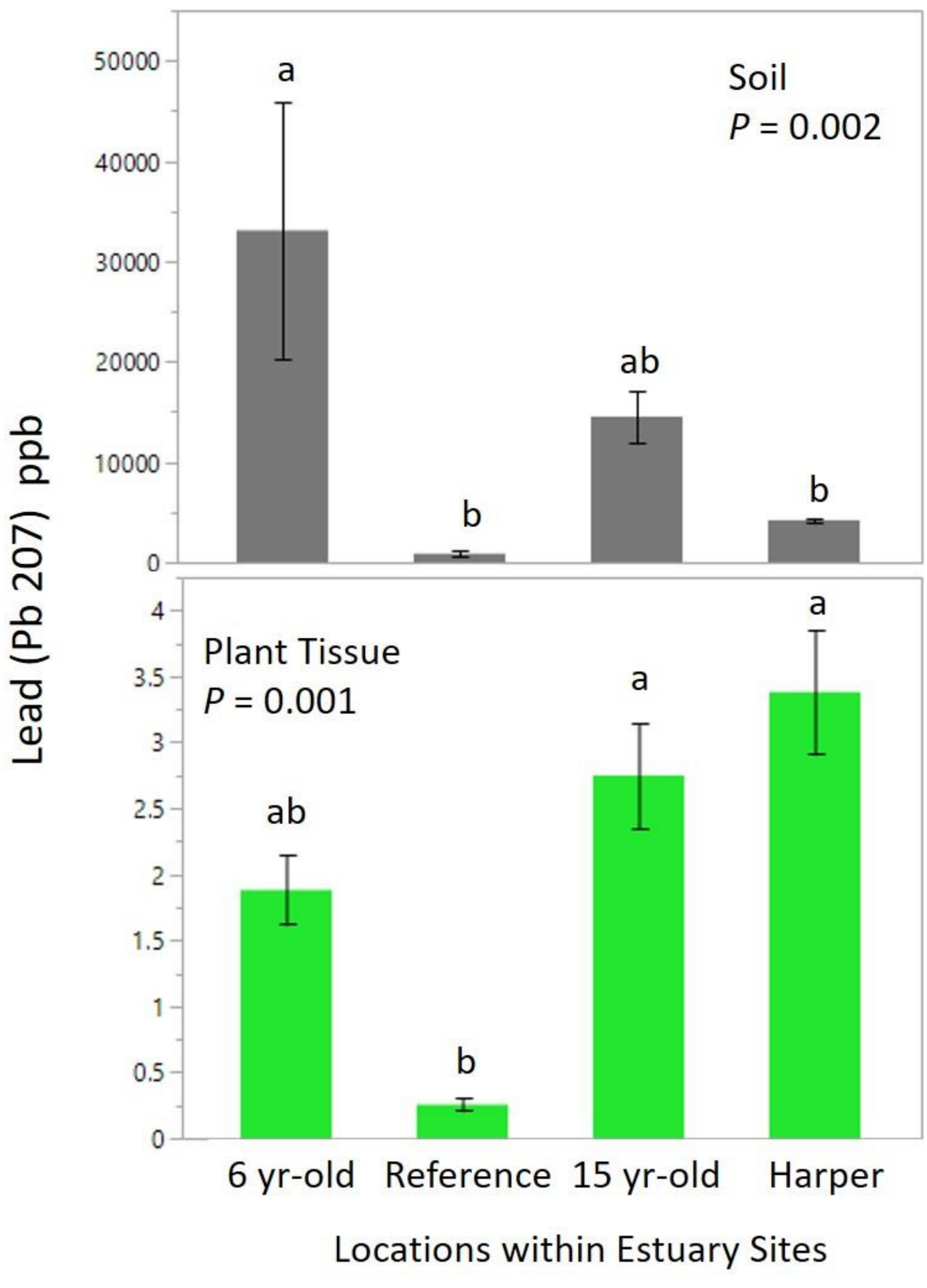

Figure 7: Concentration of lead measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in Harper and the 15-year old restoration site. However, greater lead concentrations were observed in sediments in the six-year-old restoration site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

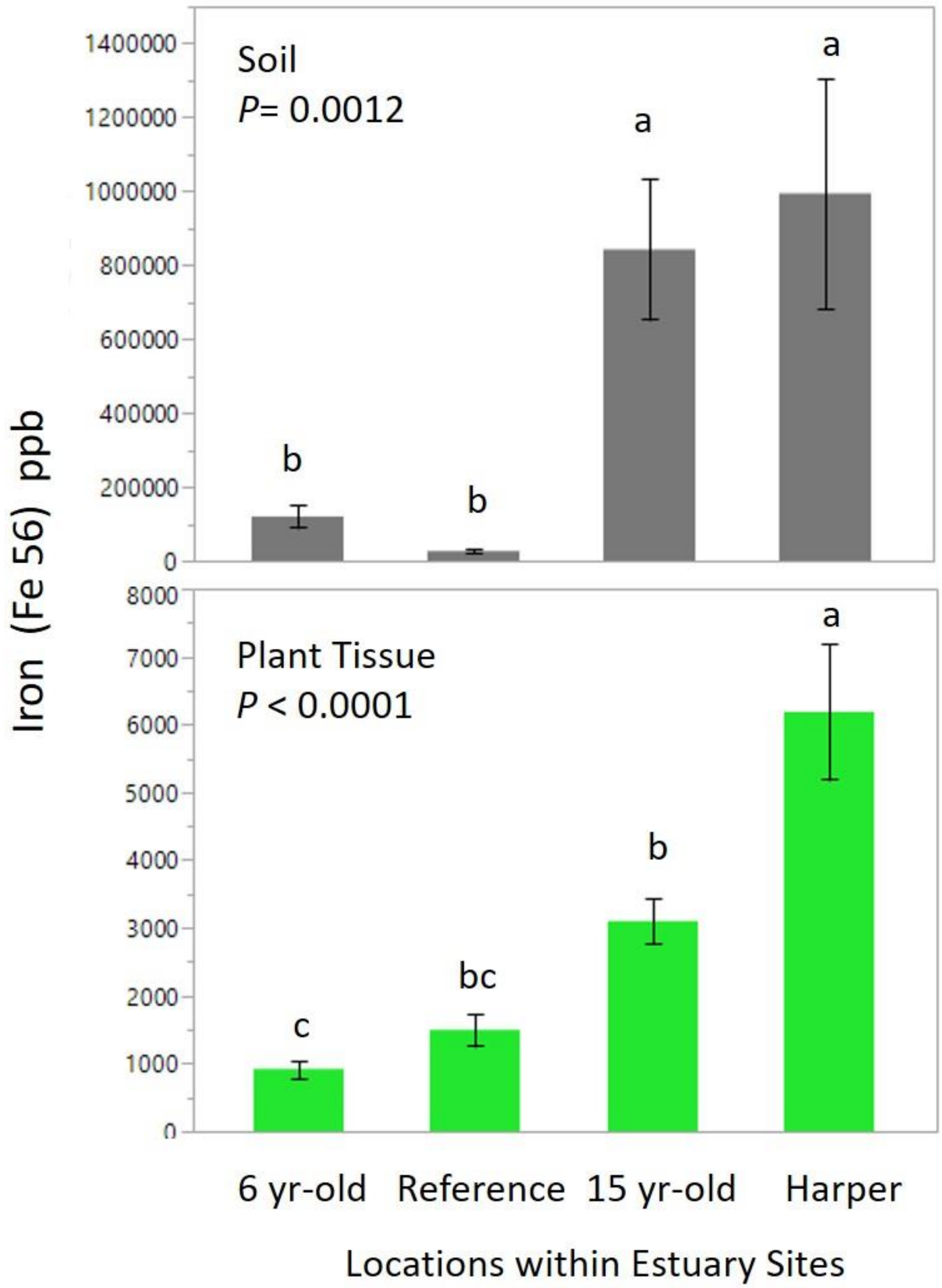

Figure 8: Concentration of iron measured in soil sediments (gray) and plant tissue (green). Greater concentrations were observed in both sediments and plant tissue in the 15-year old restoration site and in Harper Estuary. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

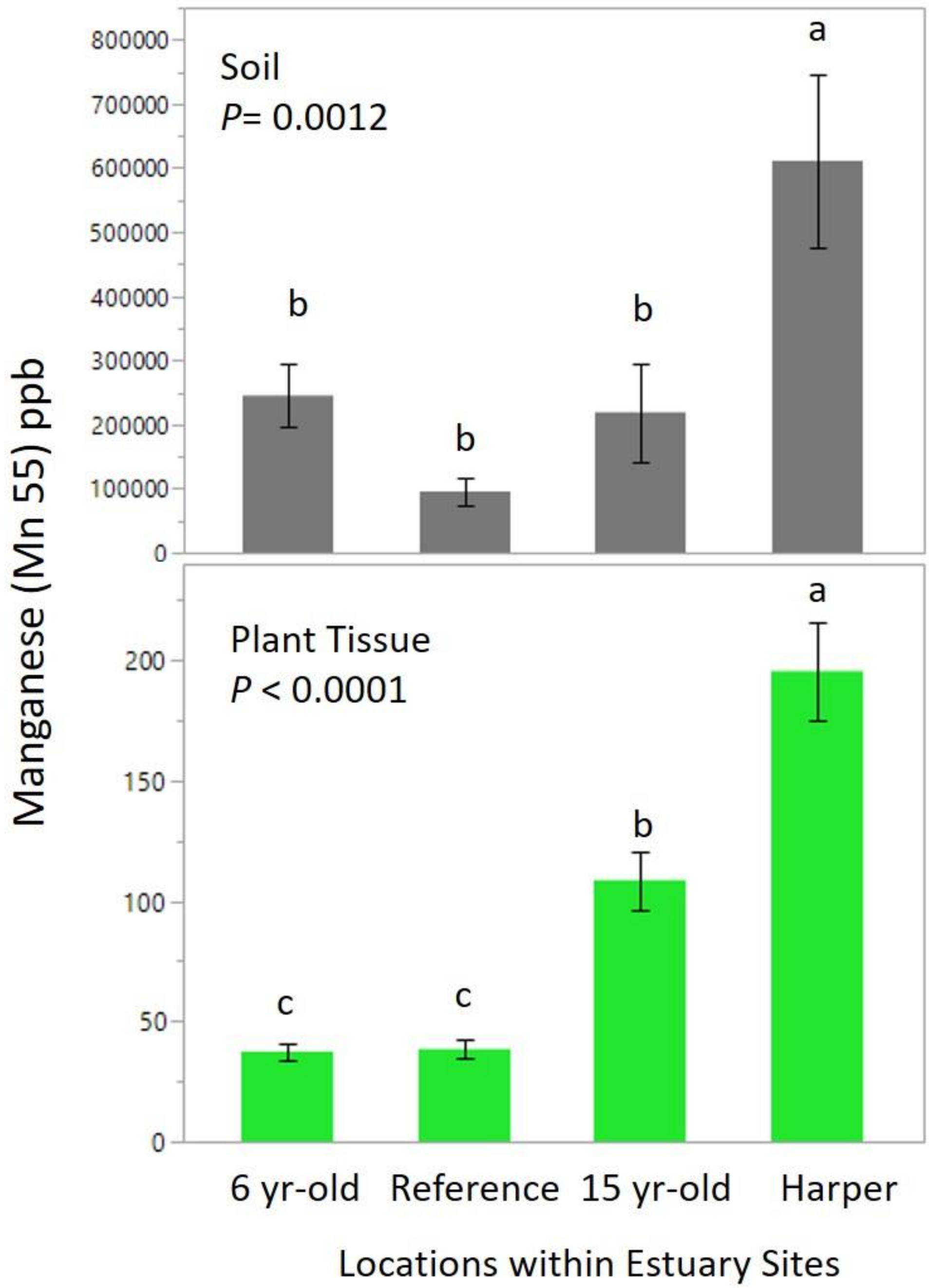

Figure 9: Concentration of manganese measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in Harper Estuary. Greater manganese concentrations were also observed in sediments in Harper. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

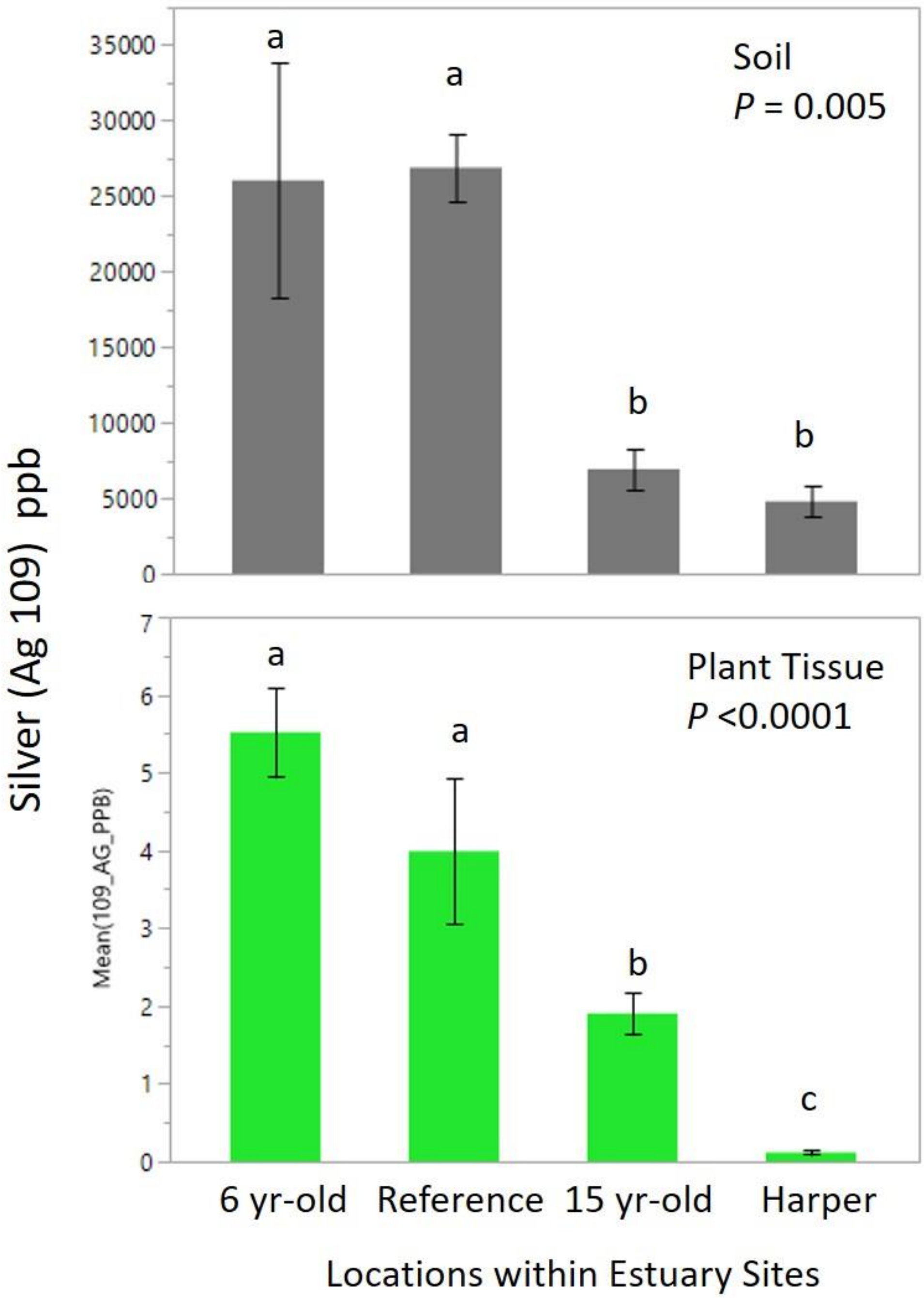

Figure 10: Concentration of silver measured in soil sediments (gray) and plant tissue (green). Greater concentrations were observed in both sediments and plant tissue in the six-year old restoration site and the non-disturbed, reference site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

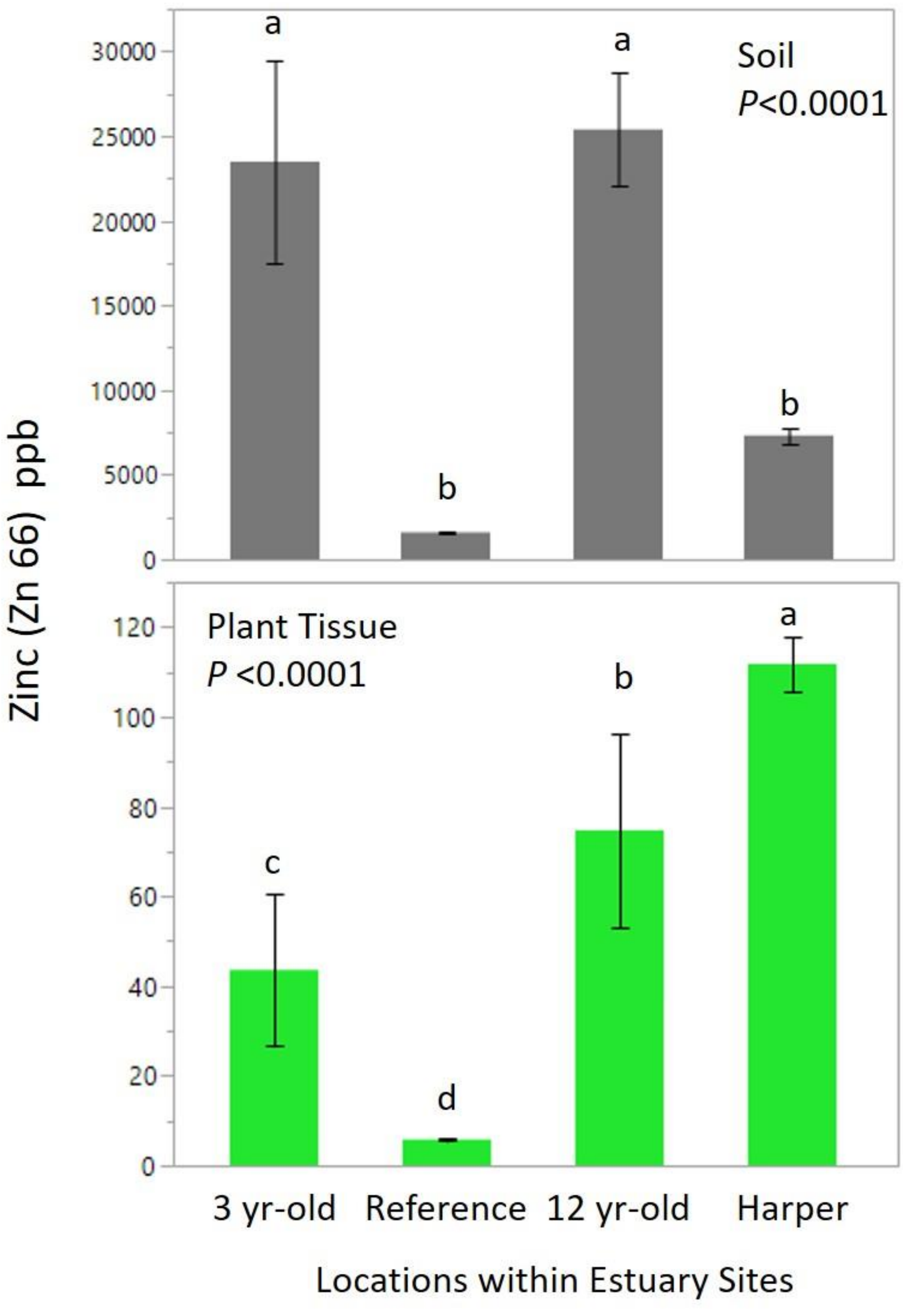

Figure 11: Concentration of zinc measured in soil sediments (gray) and plant tissue (green). Greater accumulation was noted in plant tissue in Harper Estuary. However, greater zinc concentrations were also observed in sediments in the six and 15-year-old restoration site. All p=values are displayed in the respective graph space. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

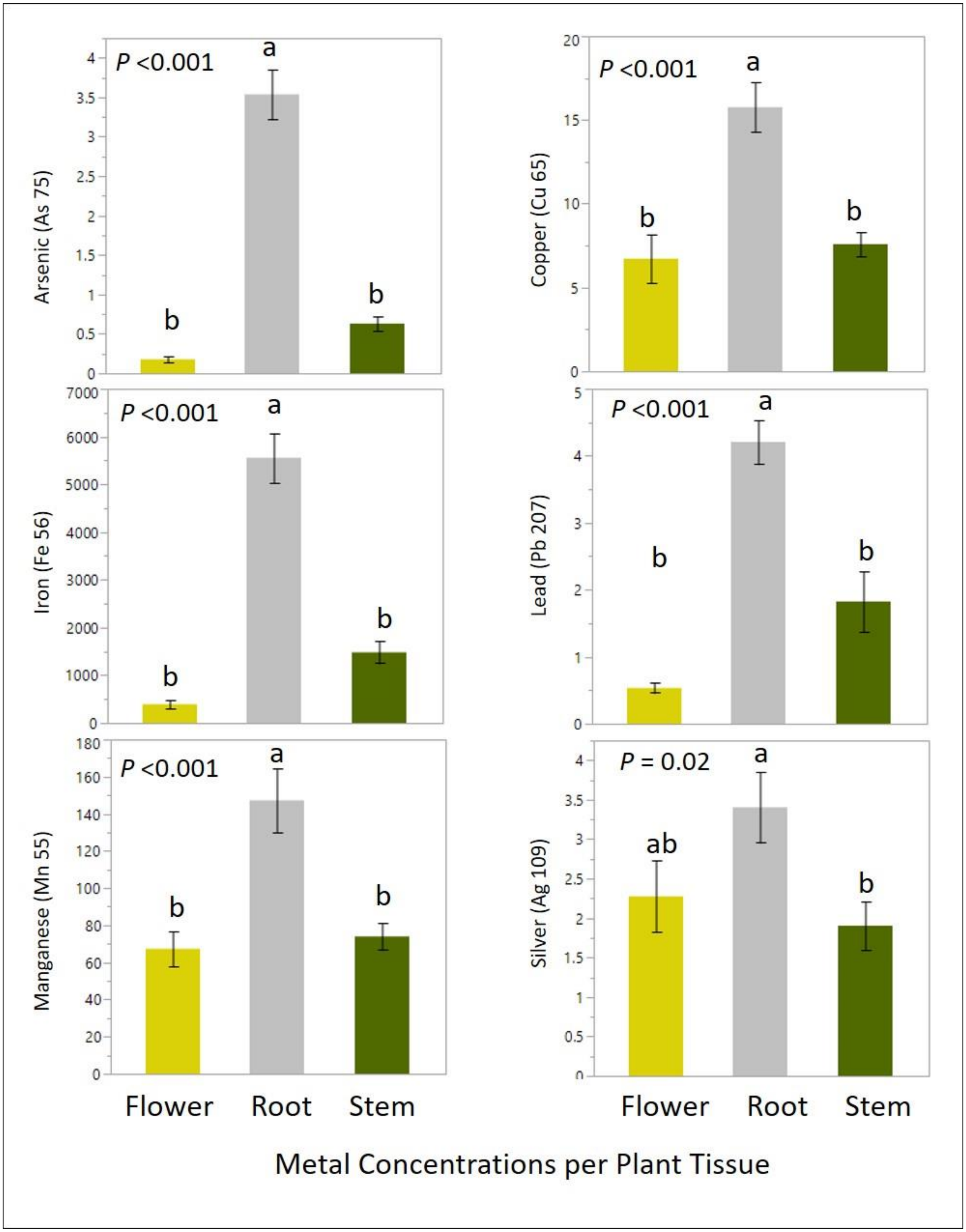

Figure 12: Bar graphs illustrate significant differences in plant sequestration of arsenic, copper, iron, lead, manganese, and silver (all p=values are displayed in the respective graph space). For each metal, plants would store accumulated metals in roots. There was one exception, silver was accumulated similarly in roots and flowers. Differences in letters indicate statistical differences determined by post-hoc pairwise comparisons (α=0.05).

Summary of Findings:

Differences in cation exchange capacity, nitrogen, soil carbon and soil organic matter existed among sites, with the lowest levels sampled from the newest post-restoration site, and highest at Harper Estuary and the Dewatto Estuary reference site. These results are consistent with other post-restoration sites over time (Borja et al. 2010), where large carbon deficits occur in initially restored systems (Craft 2007; Moreno-Mateos et al. 2012). This reduction in soil carbon and organic matter could be due to several mechanisms. For one, heavy machinery and plant removal during bridge construction were responsible for displacing fine sediment and organic matter. Secondly, the reconnection of the estuary after culvert removal promoted movement by riverine outflows, daily tides, and weather events causes displacement of lightweight, fine sediment particles into the estuary, leaving coarse sediment deposition at the tailwater of the culvert. Estuaries are characterized by the dynamic deposition and resuspension of fine sediment particles; sediment accretion naturally occurs in the low-sloped areas when water velocity is reduced. Because the sites within this study are shallow-water estuaries with flat topography, velocity of silt and fine sediment slows and allows for the accretion of sediment along estuarine edges near vegetation, which reduced the amount of fine sediment and organic accretion (Craft 2007).

None of the sites displayed carbon or SOM concentrations representative of undisturbed, temperate coastal marshes that were reviewed in the literature, which estimate normal soil carbon ranging between 12 – 20% and organic matter ranging between 22 – 35% (Mitsch and Gosselink 2015; Vincent et al. 2013). Further, it is suggested that between 18 – 26% of estuarine soil (mineral or organic) is composed of organic matter, with 21 – 25.6 % of that organic matter being comprised of carbon (Walsh et al. 2008). However, authors note that most published studies are from the eastern U.S. and will differ based on climate and dominant plant type. The reference site that was used in this study illustrated soil carbon and organic matter to be 5% and 14 %, respectively. In comparison, other sites in Western Washington that are dominated by Lyngby Sedge tend to have larger herbaceous canopies and therefore, higher soil carbon and organic matter (Poppe, unpublished data). More work is required in the region to better understand carbon and organic levels in estuaries and this study provides baseline data to compare overtime. Further, N was deficient at the newest, lower restoration site. This is presumably linked to the lack of organic matter, which is required for adequate cation exchange capacity and nutrient/plant exchange (Brady 1974). This is especially true for nitrogen, which has been reported as deficient after 30 years post-restoration (Moreno-Mateos et al. 2012).

Plants surveyed totaled 66 species between all sites and fell within the range of our statistical estimates. The 34 most common tidal marsh species formed the basis of a community plant guide for future citizen science vegetation surveys (Figure 13; Appendix A). The common estuarine species native in the Pacific Northwest were encountered in relative proportion to functional group composition typical of a temperate estuary, including species associated with culvert disturbance (Gabler et al. 2017). The Harper Estuary (pre-restoration site) is characterized by reduced channel width, increased water flow velocity, and high directional flow caused a localized scour above and below the culvert (Escarameia and May 1999). This created a bowl-shaped depression above the culvert (landward; Figure 14A) and steep banks below the culvert (seaward; Figure 14B). This change in channel morphology above the culvert caused an unnatural, slow filling of marine water during high tide, which prolonged the saline inundation resulting in mainly halophytes above the culvert, despite the freshwater input.

Harper Estuary (above the culvert) had the lowest species richness and diversity of species representing low marsh colonizers such as pickleweed, fleshy jaumea, salt marsh rush, and saltgrass. This illustrates the significant alteration of tidal flushing, which increases marsh salinity and impedes the development of a salinity gradient, which drive a diverse assemblage of plant species (Moffett and

Gorelick 2016). In contrast, below the culvert was deeply channelized, resulting in a vertical gradient with a perched landform disconnected from tidal influence, as evident by the presence of salt intolerant invasive species and woody riparian plants. Also deeply channelized was the intermediate site with the lower marsh vegetation comprised of halophytic forbs, graminoids, and rushes on the seaward side, and riparian woody species present above the bridge (landward side). The primary difference in this site was the size of the bridge (7 m), which resulted in a deep channelization and steep vertical gradient disconnected from tidal influence, as evidenced by the riparian plant communities. This is in contrast to the undisturbed site at Dewatto Estuary, where natural flood plains result in tidal flushing and flood plains that result in native, salt marsh vegetation (Figure 15).


Figure 13. Harper Estuary plant walk & survey led by professor Jenise Bauman, Western Washington University in the Huxley College of the Environment. This created a community of citizens that became a part of the vegetation monitoring effort at Harper Estuary. Community members walked the site and took part in a citizen science plant survey on Saturday, September 14, 2019.

Figure 14. The Harper Estuary (pre-restoration site) is characterized by reduced channel width, increased water flow velocity, and high directional flow caused a localized scour above and below the culvert. This creates a bowl-shaped depression above the culvert (landward; Figure 14A) and steep banks below the culvert (seaward; Figure 14B). This obstruction results in the loss of tidal flushing that may accumulate the high salinity concentrations. In addition, this may also impede the dilution of metals that may be a residual impact from the former brick company.

Figure 15. Dewatto Estuary represented the undisturbed site, where natural flood plains result in tidal flushing and flood plains that result in native, salt marsh vegetation (data not shown).

When comparing estuaries, Harper Estuary had significantly higher summer temperatures, nitrates, dissolved solids, and salinity than the other restored or non-disturbed site. As mentions above, this is presumably contributed by the lack of tidal flushing due to the culvert and subsequent morphology of the channels in the estuary. Harper estuary had a greater plant bioaccumulation of arsenic, cadmium, copper, lead, iron, manganese, and zinc. This is due to the higher rates of dissolved solids in the water column and higher levels of organic matter in the sediments when compared to the restored sites. It is noted that the restored sites were high in arsenic, cadmium, and zinc. The most recently restored site had the highest concentrations of lead and silver in sediments. The undisturbed reference site had much lower metals present in sediments with one exception, silver. Plants sequestered higher concentrations of arsenic, copper, iron, lead, manganese, and silver in root tissue when compared to stems and flower tissue.

In summary, soil carbon and organic matter are initially lost during restoration with no sites having ranges comparable to natural estuaries. Borja et al. (2010) suggest recovery from sediment modification and habitat creation is estimated to take at least two decades. To increase organic recruitment, engineering large wood and root wads coupled with the installation of an organic mesh to capture fine sediments and organic particles may speed up plant establishment and organic matter accretion. Plant communities do not appear to homogenize between locations (above and below). On the interior of the bridges, there is a development of a salinity gradient, which is a common component of salt marshes within pocket estuaries. However, vertical gradients, observed at Harper

Estuary and the restored estuary sites, maintained by deep channelization at the shoreline and resulted in perched vegetation communities that are removed from the tidal influence. This indicates that culvert removal is a necessity for near shore and marsh conservation. In addition, and larger span bridge length may be required to facilitate the recovery of natural floodplains to adequately create marsh habitat in lowland pocket.

In restoration projects in Western Washington, seeding or planting of pickleweed, saltgrass, seaside plantain, and Lyngby's sedge could be initiated upon restoration. After the development of the salinity gradient, woody plantings (e.g. Ocean Spray, Hooker's Willow, Oregon Ash, Madrone, and Shore Pine) can be incorporated along the vertical gradient where inundation is infrequent. Important attributes of faster plant establishment will slow the velocity of water encouraging fine sediment particles to settle. In addition, plant roots create a biological matrix for soil microbes and create smaller pore spaces for proper aeration of roots, which supports a positive feedback of organic matter deposition and a sooner return of ecosystem services, such as the bioaccumulation of metals.

Acknowledgements:

Funding for this estuary monitoring research or report was provided by the Washington Department of Ecology [Grant Agreement No. OTGP-2018-KiCoCD-00007]. Author thanks Christina Kereki with Kitsap County for overall project assistance. I would also like to thank the field support by WWU students Shannon Call, Maggy Critchlow, Tera Dummitt, Jason Edwards, David Johnson, Andrew McCay, Brianna Thomas- Ross, Caitlin Sidhu, and Justice Serafin. Data will be continued to be analyzed and presented by students at the 2021 Virtual Salmon Recovery Conference and Western Washington University's Scholar Week.

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Appendix A:

Estuary and Tidal Salt Marshes

Common Plants of Western Washington

Dr. Jenise M. Bauman and Brianna Thomas-Ross

Acknowledgments: Burke Museum Herbarium (photos credited by individual),

Kitsap County Department of Community Development, and
Plants of the pacific Northwest by Pojar and MacKinnon

Tidal Salt Marshes:

Found throughout the world along coastlines that are protected from wave and storm energy

Ecological structure and function of salt marshes is similar

Complex Zonation of vegetation, animals and microbes based on alterations in:

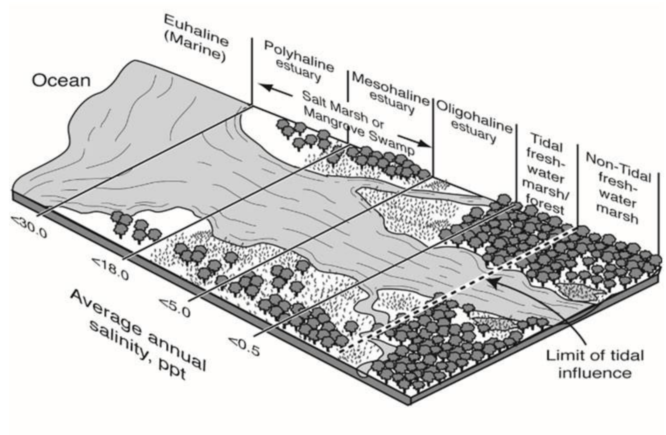
- Salinity
- Drying and submergence
- Daily temperature

Tidal Salt Marshes:

Interface between terrestrial and marine habitats

The physical features of tides, sediments, freshwater inputs, and shoreline structure determine the development and extent of saltmarsh

Inundated during high tide – but not flooded during low tide

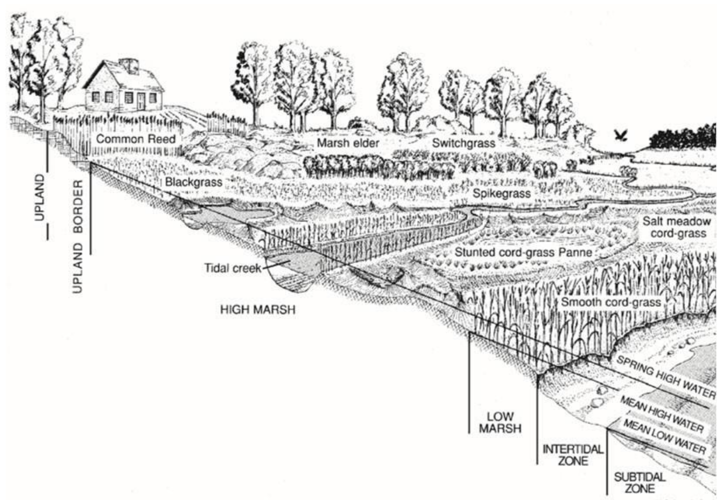


Tidal Salt Marshes

Vegetation:

Plants have adapted to salinity, periodic inundation, temperature extremes

Water water everywhere but not a drop to drink! Plants must adapt to extreme salinities by expending energy to increase their internal osmotic concentration in order to take up water.



Silver Burweed (*Ambrosia chamissonis*)

A. Plant: Succulent perennial, silvery, finely pubescent and forms large clumps

B. Leaves: Mostly alternate, petiolate, the toothed to pinnately dissected

C. Flowers: Leafless, terminal spikes maturing into a sharp bur consisting of a series of flattened prickles

Habitat: Sandy Beaches

Photo credits: A. Ben Legler B. G.D. Carr C. Ben Legler

Pickleweed (*Salicornia virginica)*

A. Plant: Succulent perennial,

glaucous, bluish to purple

B. Leaves: Succulent, mealy, cylindrical scales

C. Flowers: Inconspicuous at end of branches, greenish yellow matures into bladder like scales

Habitat: Salt marshes, tide flats, waveless beaches

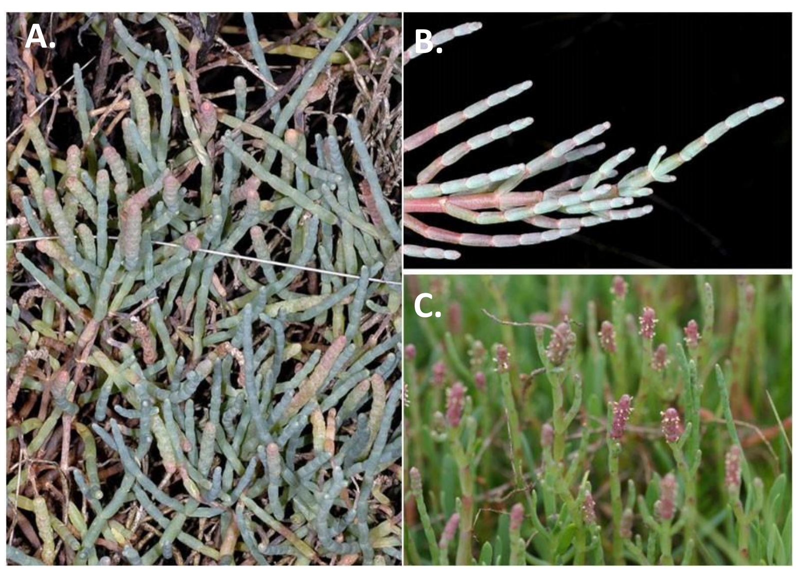


Photo credits: A. and B. G.D. Carr C. Dana Visalli

Douglas' Aster (*Symphyotrichum subspicatum)*

A. Plant: Perennial herb, stiff stems, leafy stems, hairy, and freely branching

B. Leaves: Lower lanced-shaped, middle oblong or narrowly elliptic, toothed, and hairless

C. Flowers: Composite, blue to purple, disk, several on a leafy-bracted stalk

D. Habitat: Beaches, meadows, streambanks, moist clearings

Photo credits: A. Dana Visalli, B. G.D. Carr and C. C.J. Antieau

Gumweed *(Grindelia integrifolia)*

A. Plant: Perennial herb, stout branched stem-base, stems leafy and hairy

B. Leaves: mostly alternate, petiolate, the toothed to pinnately dissected, stalkless

C. Flowers: Large 'sunflower like' flowers, sticky glandular, yellow disk flower, green tips

Habitat: Beaches, salt marshes, mostly maritime habitats

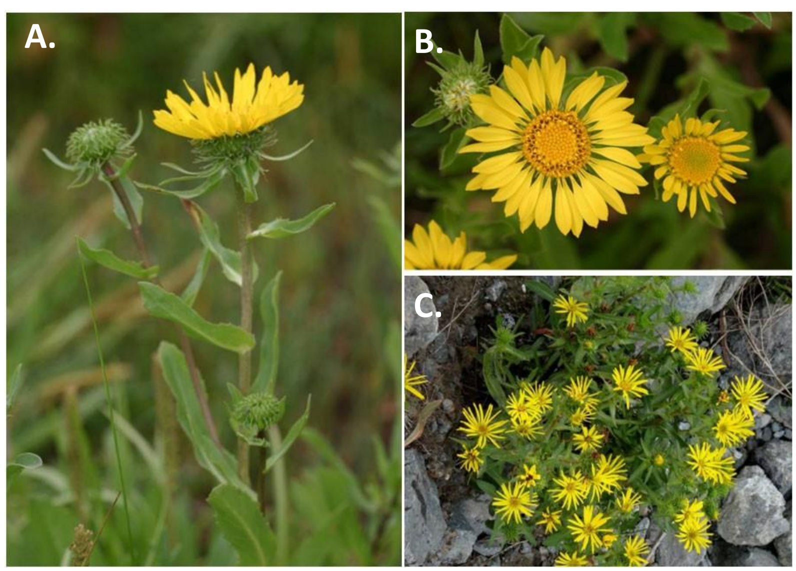


Photo credits: A. and B. Dana Visalli C. Brian Luther

Purple Leaved Willowherb *(Epilobium ciliatum)*

A. Plant: Perennial, simple below and freely-branched above, puberulent, glandular above

B. Leaves: Inflorescence of racemes terminal on the branches, purplish, notched

C. Flowers: Large 'sunflower like' flowers, sticky glandular, yellow disk flower, green tips

Habitat: Moist soil from lowlands to middle elevations

Photo credits: A. and B. G.D Carr C. Richard Old

Pacific Silverweed *(Potentilla anserina)*

A. Plant: Perennial, usually low growing 'strawberry like'

B. Leaves: Underside leaves are wooly and silver in color, basal, compound, pinnate

C. Flowers: Yellow, small, glossy, oval petals, 'buttercup like'

Habitat: Marsh edges, stream sides, beaches, dunes

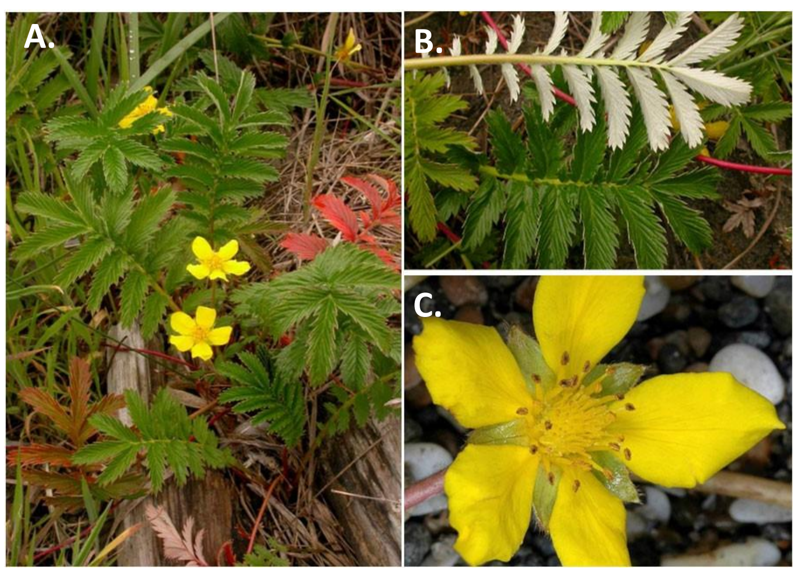


Photo credits: A. and B. Ben Legler C. G.D. Carr

Orache (*Atriplex petula*)

A. Plant: Annual, covered in a whitish/mealy substance when young, hairless with age, upright stems, branched, leafy

B. Leaves: Lanced shaped to linear or oblong, rounded to arrowhead, lower leaves opposite, upper alternate

C. Flowers: Greenish purple, tiny, spikes at the end of branches

Habitat: Saline soils

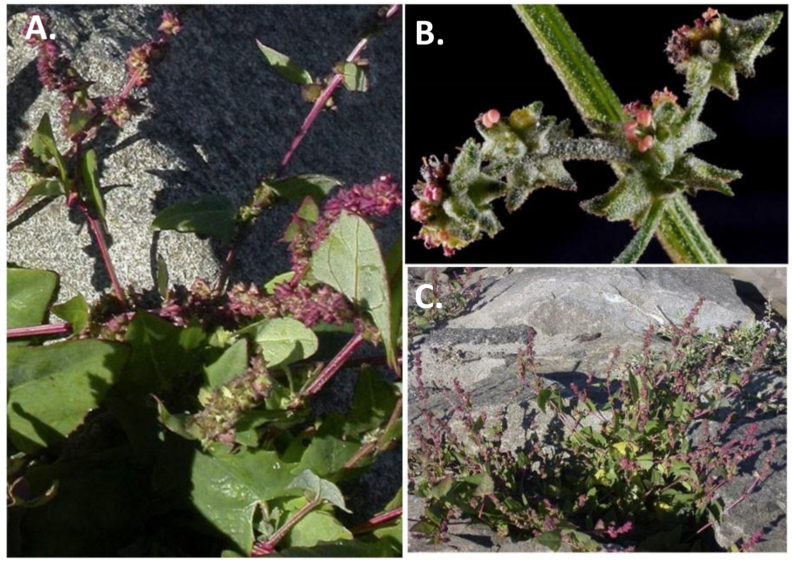


Photo credits: A. B. and C. G.D. Carr C.

Montia (*Montia Linearis*)

A. Plant: Annual, stems ascend to erect, several or sometimes single, branched or unbranched from base

B. Leaves: Alternate, linear

C. Flowers: White, one sided clusters

Habitat: Moist to dry, sandy to rocky

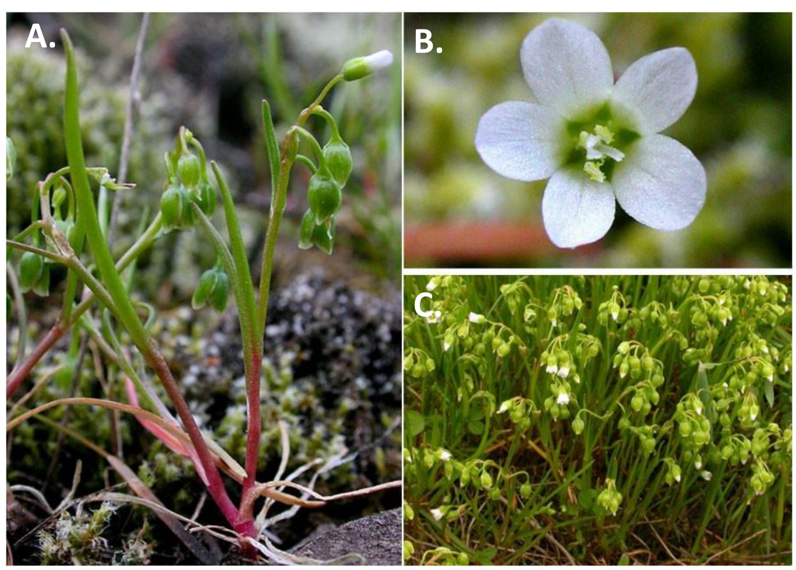


Photo credits: A. B. and C. Ben Legler

Saltmarsh Sandspurry (*Spergularia salina*)

A. Plant: Annual, succulent, multi ascending erect stems

B. Leaves: Fleshy, crowded, opposite, blunt/pointed at tip

C. Flowers: White to deep pink, abundant, sepals as long or shorter than petals

Habitat: Saline or brackish areas along coast and alkaline areas inland

Photo credits: A. and B. Ben Legler C. Richard Old

Canada Sandspurry (*Spergularia canadensis)*

A. Plant: Annual, succulent, sprawling, leafy stems, clumped

B. Leaves: Fleshy, crowded, opposite, blunt or pointed at tip

C. Flowers: Whitish, abundant, sepals as long or longer than petals

Habitat: Sea beaches, tidal marshes, mudflats, brackish soil

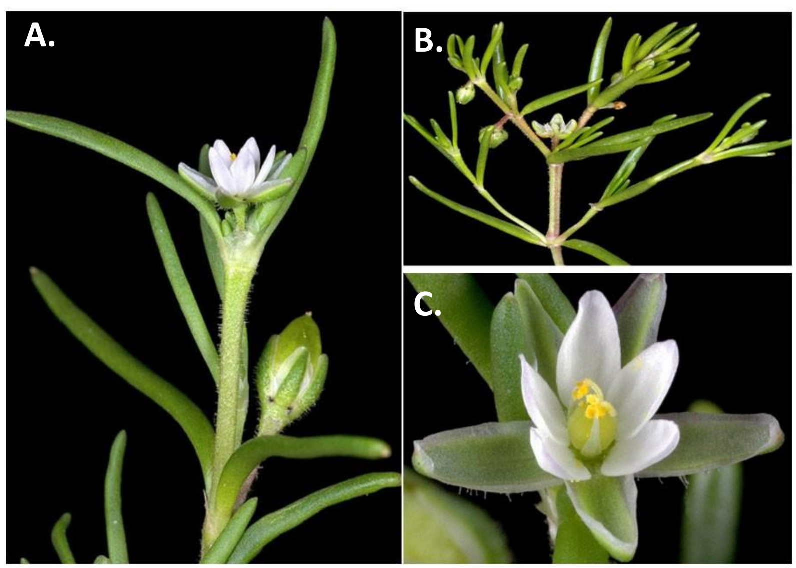


Photo credits: A. B. and C. G.D. Carr

Fleshy Jaumea (*Jaumea carnosa*)

A. Plant: Perennial, succulent-like, stems weak, often almost flat on the ground

B. Leaves: Leaves linear to narrowly oblong, rounded tips, fused to stems

C. Flowers: Yellow flower heads small, deciduous, fleshy, usually purplish bracts

Habitat: Tidal flats and marshes.

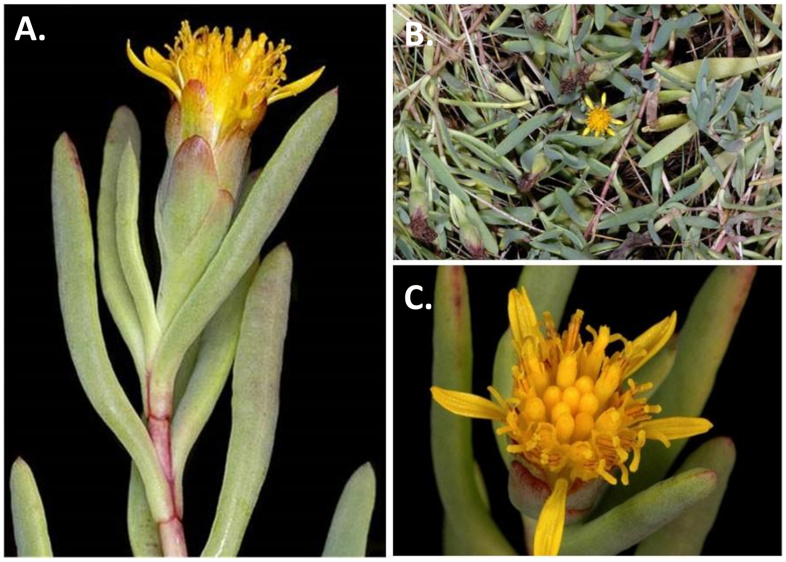


Photo credits: A. B. and C. G.D. Carr

Seabeach Sandwort *(Honkenya peploides)*

A. Plant: Perennial, glabrous, mat-forming, yellowish-green, fleshy, trailing stems

B. Leaves: Leaves lanceolate to ovate, broad, smaller on the axillary branches.

C. Flowers: Greenish, inconspicuous, single in the leaf axils or stem branches, white petals

Habitat: Coastal beaches, strands, and sand dunes.

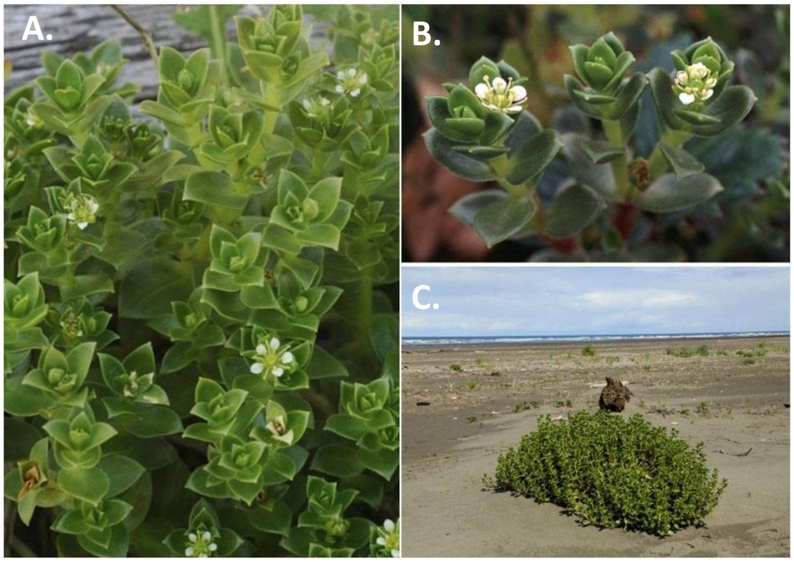


Photo credits: A. Ben Legler B. Jim Riley C. Donovan Tracy

American Sea-rocket *(Cakile edentula)*

A. Plant: Annual, glabrous, fleshy, stems freely-branched, decumbent at base

B. Leaves: Alternate, deeply scalloped to wavy- serrate, narrowed to a broad petiole

C. Flowers: White to purplish-tinge, long-clawed, several in short clusters

Habitat: Marine water shorelines in sand or gravel.

Photo credits: A. Ben Legler B. and C. G.D. Carr

Sea Milkwort *(Lysimachia maritima)*

A. Plant: Perennial, hairless, fleshy, stems leafy

B. Leaves: Opposite low on stem, alternate above, oval to oblong, rounded at tip, stalkless

C. Flowers: White or pinkish, cup-shaped, single and stalkless in leaf axils

Habitat: Tideflats, salt marshes, sea beaches

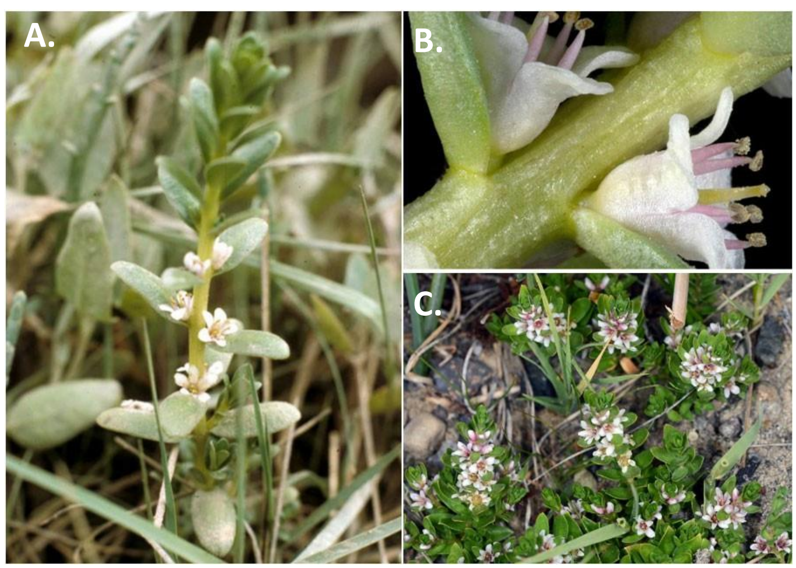


Photo credits: A. Fred Weinmann B. and C. G.D. Carr

Sea Plantain *(Plantago maritima)*

A. Plant: Perennial, slightly wooly at crown, flowering stems slightly longer than leaves

B. Leaves: All basal, fleshy long linear, mostly hairless

C. Flowers: Small greenish-brown, inconspicuous, dense spikes

Habitat: Salt marshes, rocky shores, and beaches

Photo credits: A. Ben Legler B. G.D. Carr C. Paul Slitcher

Ribwort *(Plantago lanceolata)*

A. Plant: Perennial, short, stout, woody base, tan-woolly at the crown, the several scapes, grooved and rigid

B. Leaves: Leaves all basal, woolly to glabrous, lance-elliptic, acute

C. Flowers: Dense, bracteate, cylindric spike

Habitat: Roadsides, fields and other disturbed, open areas

Photo credits: A. Harry Thomas B. Ron Bockelman C. Roger T. George

Seaside Arrowgrass *(Triglochin maritima)*

A. Plant: Perennial, hairless, fleshy, forms large clumps

B. Leaves: All basal, upright to spreading, half round to flattened

C. Flowers: Compact racemes extending half the length of the plant, tiny green to purplish flowers

Habitat: Tidal marshes and mudflats, brackish meadows, sloughs

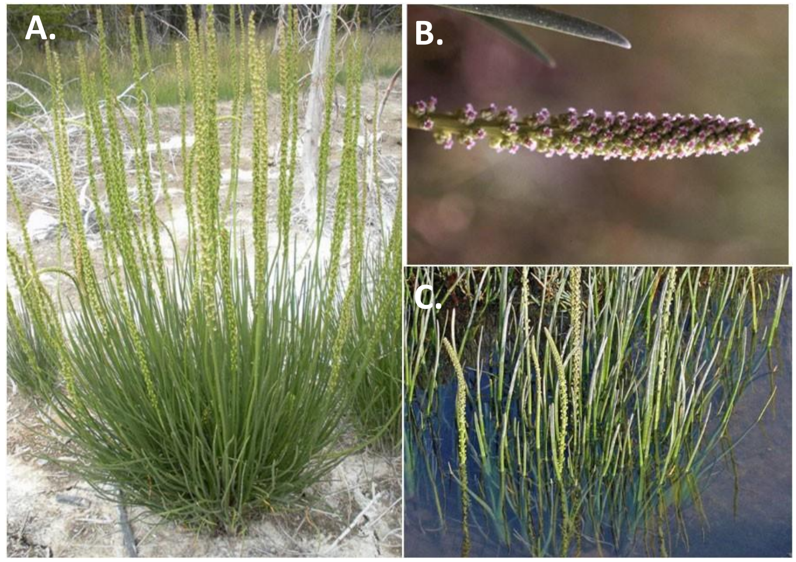


Photo credits: A. Clayton J. Antieau B. Jim Riley and C. G.D. Carr

Baltic Rush *(Juncus balticus)*

A. Plant: Perennial, long slender tepals, teret stems, smooth, thick at base

B. Leaves: Basal sheaths bladeless or with a ‘bristle like’ blade

C. Flowers: Clustered,, lateral inflorescence, sharp pointed, perianth greenish to dark brown

Habitat: fresh and saltwater wetlands

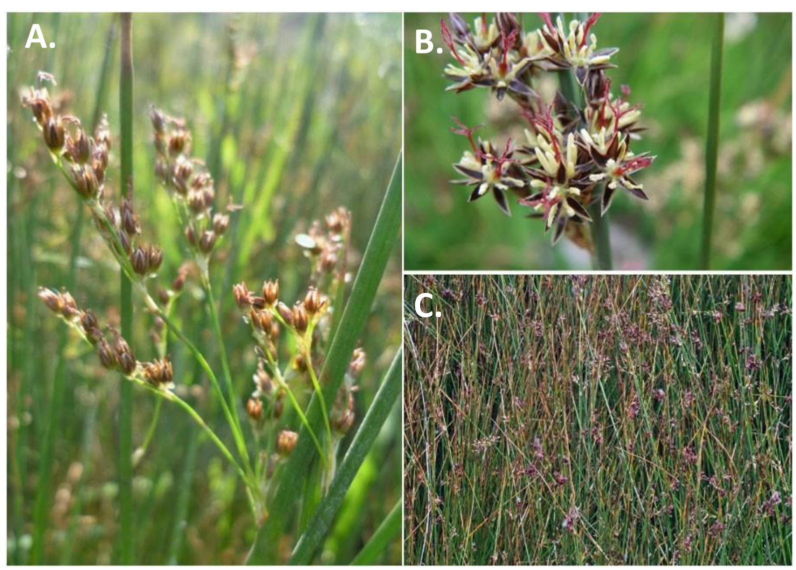


Photo credits: A. Thayne Tuason B. Ron Bockelman and C. Robert L. Carr

Saltmeadow Rush *(Juncus gerardii)*

A. Plant: Perennial, 6 segments, anthers much longer than the filaments

B. Leaves: Flat blades, alternate leaves, sheathing bases, mid length of flowering stem

C. Flowers: Inflorescence many-flowered, loosely cymose, dark brown with a greenish mid-stripe, blunt, hooded at tip

Habitat: Coastal salt marshes

Photo credits: A. and B. Fred Weinmann

Needle Spikerush *(Eleocharis acicularis)*

A. Plant: Perennial, grass-like stems, stems oval at cross section, arises singly or in clusters from long rhizomes

B. Leaves: All basal and reduced to mere sheaths

C. Flowers: Single terminal spikelet, long, brown, lance to egg shaped

Habitat: Marshes, muddy shores, and other wet places

Photo credits: A. Ben Legler B. G.D. Carr and C. Richard Old

Seacoast Bulrush *(Bolboschoenus maritimus)*

A. Plant: Perennial, heavily rhizomatous, tall and forms dense stands

B. Leaves: Well developed, elongated, flat

C. Flowers: Several to many spikelets aggregated in head-like terminal cluster cradled by leaf-like bracts

Habitat: Salt marshes, wet meadows, especially in alkaline or saline areas

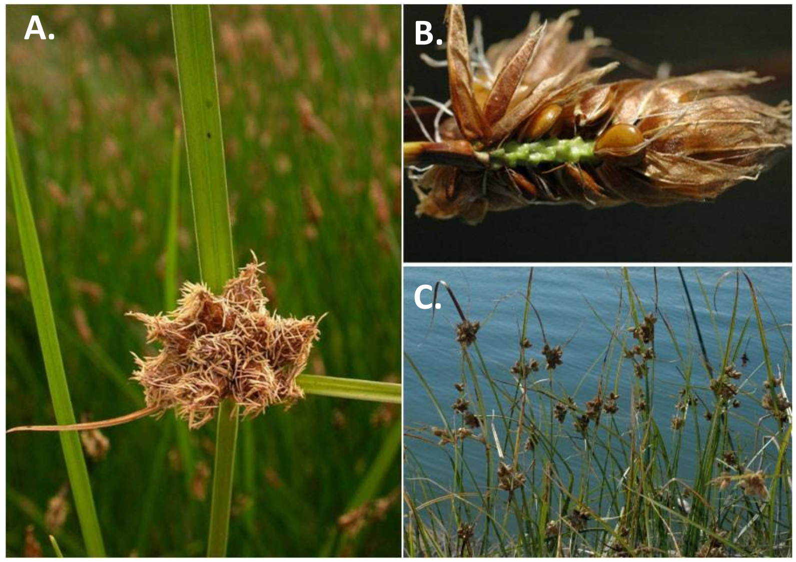


Photo credits: A. B. and C. Ben Legler

Hardstem Bulrush (*Schoenoplectus acutus*)

A. Plant: Herbaceous perennials from rhizomes, thick at base, stout

B. Leaves: Few, toward the base of the culm, with well-developed sheath and short blade

C. Flowers: Clustered spikelets, dull gray- brown

Habitat: Pond and lake margins, wetland and riparian

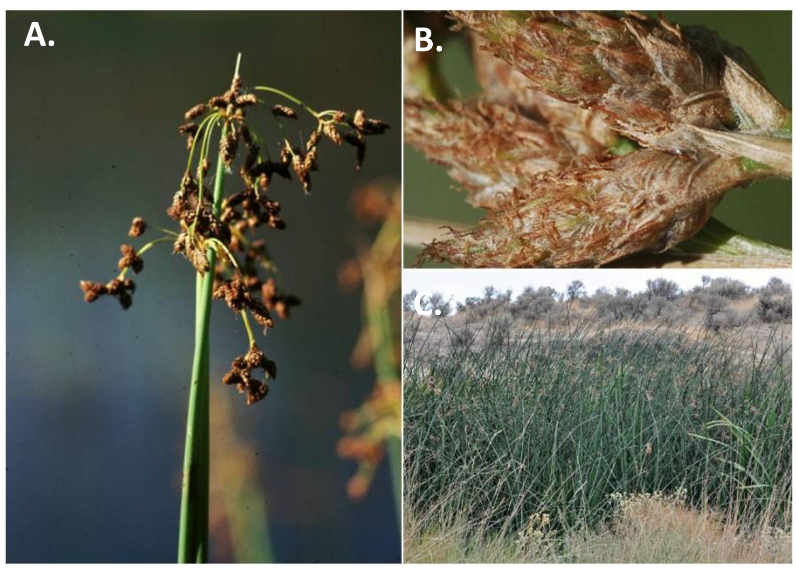


Photo credits: A. Fred Weinmann B. Ben Legler and Robert L. Carr

American Bulrush *(Schoenoplectus americanus)*

A. Plant: Perennial, stems single or in small groups, sharply triangular, erect

B. Leaves: Firm, long, strongly folded/channeled, sometimes flat, narrow

C. Flowers: Seedlike, pointy tipped achenes, lens-shaped, scales, brown/blackish/purple

Habitat: Fresh and brackish marshes, shores, wet meadows, ditches

Photo credits: A. B. and C. Bud Kovalchik

Lyngbye Sedge *(Carex lyngbyei)*

A. Plant: Stems single or in clumps, purplish-brown at base, non-shreddy

B. Leaves: Reddish-brown sheaths, conspicuous old leaves, flat, margins rolled under, wide, abruptly pointed

C. Flowers: Spikes on all stalks, lowest bract is ‘leaf-like’

Habitat: Tidal marshes and flats, estuarine meadows, gravel or pebble beaches

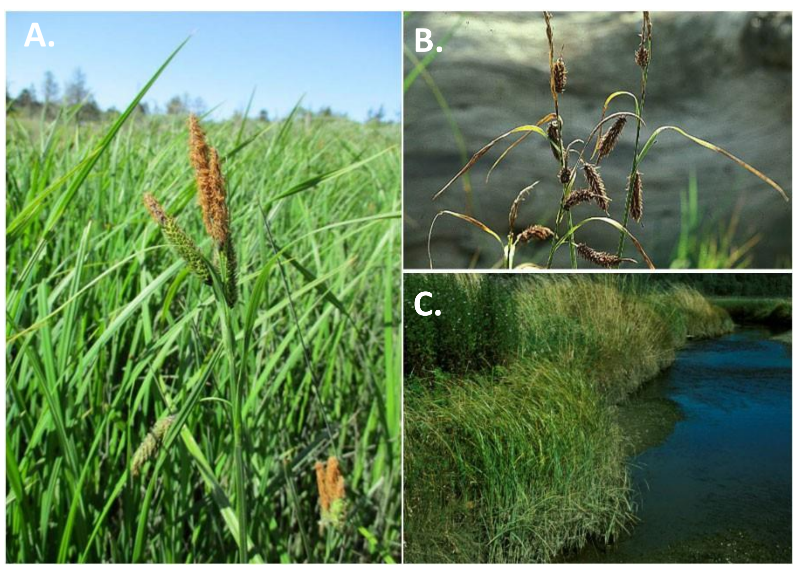


Photo credits: A. Sean Patrick B. Fred Weinmann and C. Clayton J. Antieau

Western Lilaeopsis *(Lilaeopsis occidentalis)*

A. Plant: Perennial herb, small, erect stem lacking

B. Leaves: Narrow, hollow tubes, 5-11 partitions

C. Flowers: White inconspicuous, loose clusters on pedicels, fleshy at base

Habitat: Coastal marshes and saltwater tideflats; maritime

Photo credits: A. Ben Legler B. G.D. Carr and C. Fred Weinmann

Saltmarsh Dodder *(Cuscuta pacifica)*

A. Plant: Perennial herb, parasitic, twinning; slender, orange, pinkish-yellow to white glabrous stems, often forming large mats.

B. Leaves: Reduced to tiny scales

C. Flowers: Whitish cream or yellow, small, fused, fleshy, stalkless, clustered

Habitat: Coastal marshes and saltwater tideflats, parasitic

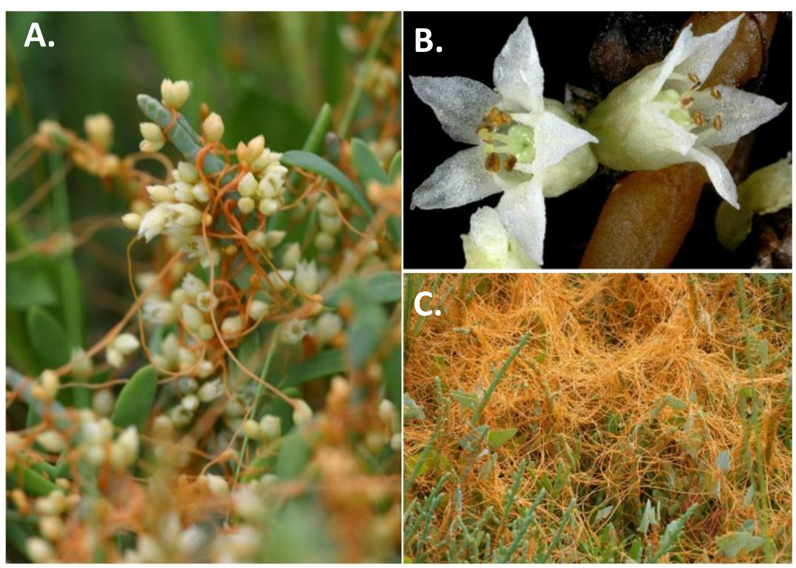
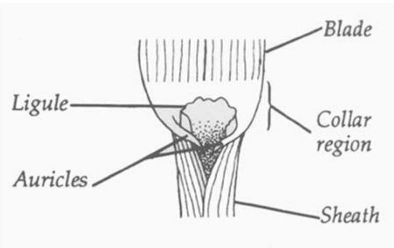
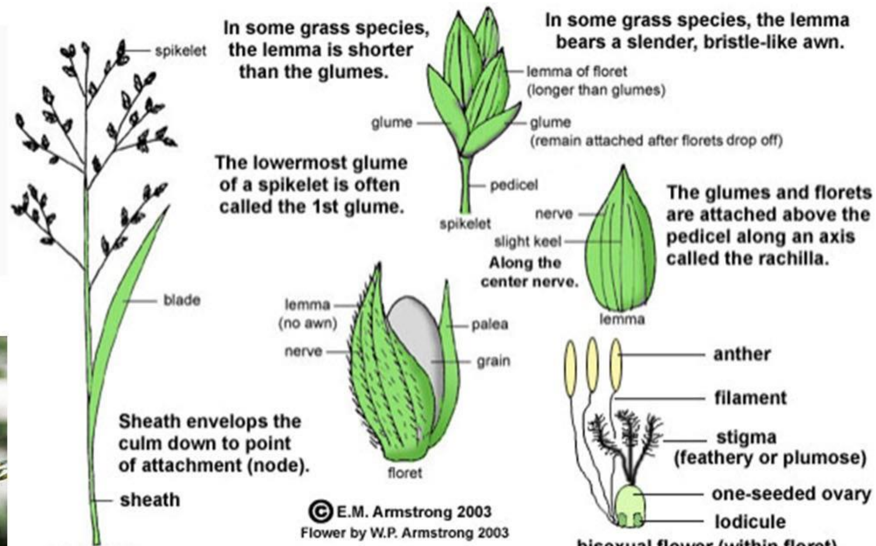


Photo credits: A. Dana Visalli B. G.D. Carr and C. Regina Johnson

Grass Terminology:





Meadow Barley *(Hordeum brachyantherum)*

A. Plant: Perennial, tuft, erect but bent at base

B. Leaves: Reddish-brown sheaths, hairless to spreading hairy, no auricles, short ligules, frilly at tip

C. Flowers: Spike, usually erect, brittle, glumes slender and 'awn-like'

Habitat: Ocean beaches to mountain meadows, usually where moist

Photo credits: A. and B. Fred Weinmann and C. Robert L. Carr

Dunegrass *(Leymus mollis)*

A. Plant: Perennial, thick rhizomes, forms large clumps, tall, usually finely hairy above

B. Leaves: Sheaths open, glabrous, auricles developed on some leaves, very short, tough blades, flat

C. Flowers: Spike, stout, erect, glumes and lummas are soft-hairy

Habitat: Coastal sand dunes, marshes, headlands

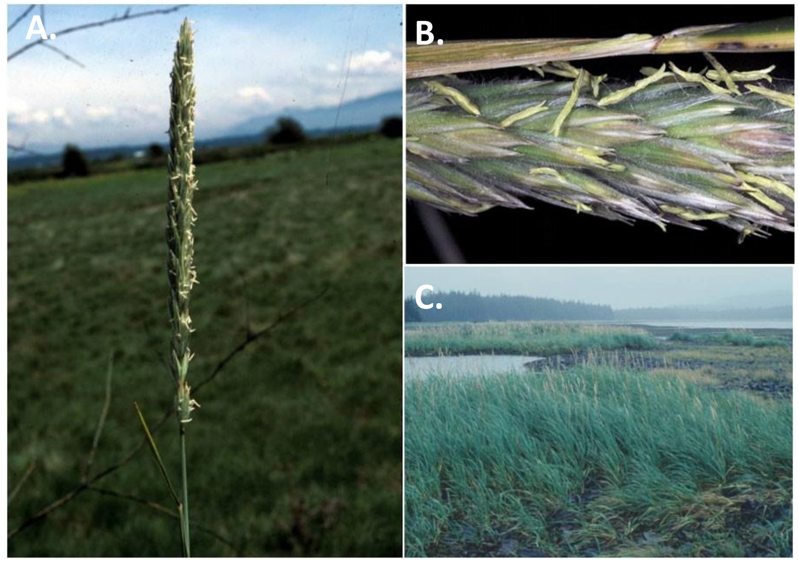


Photo credits: A. Fred Weinmann B. G.D. Carr and C. Clayton J. Antieau

European Beachgrass *(Ammophila arenaria)*

A. Plant: Perennial, aggressively tall, connected by tough rhizomes

B. Leaves: Sheaths open smooth, narrow, inrolled, long, stiff, no auricles, sharp pointed

C. Flowers: Dense and spike-like panicle shorter than the glumes, crowded spikelets

Habitat: Beaches and dunes

Photo credits: A. Ben Legler B. G.D. Carr and C. Richard Old

Tufted Hair Grass *(Deschampsia caespitosa)*

A. Plant: Perennial, densely tufted, numerous stems

B. Leaves: Flat to folded, narrow, stiff, prominent ligules, golden hue in the late summer and early fall

C. Flowers: Panicle, open loose, often nodding, spikelets are bronze and glistening, hairy at base, darken with age

Habitat: Common in moist areas from sea level to alpine

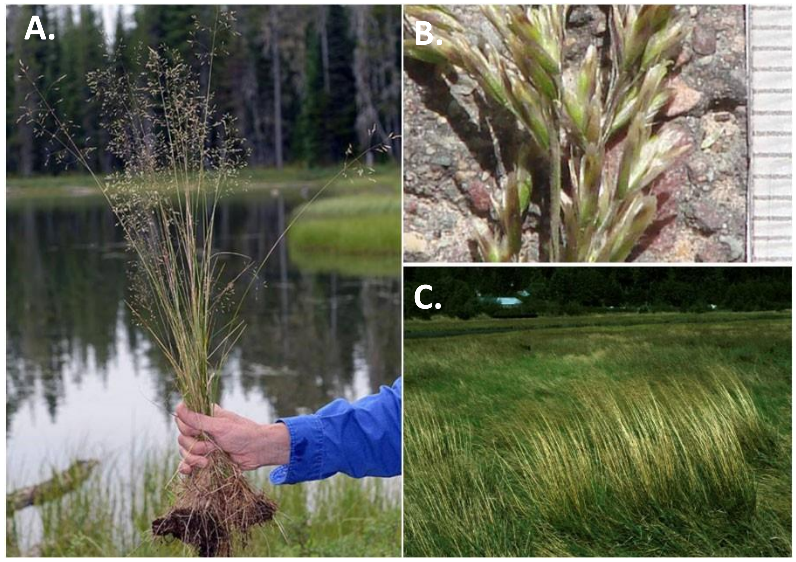


Photo credits: A. G.D. Carr B. Craig Althen and C. Clayton J. Antieau

Seashore Saltgrass *(Distichilis spicata)*

A. Plant: Perennial, sod-forming, solid stems and vigorous

B. Leaves: Bilateral symmetry, yellowish-green, short, stiff and erect, persistent old leaves, no auricles

C. Flowers: Panicles are robust and flower bearing; florets are compressed with tightly packed lemmas

Habitat: Coastal beaches and salt marshes

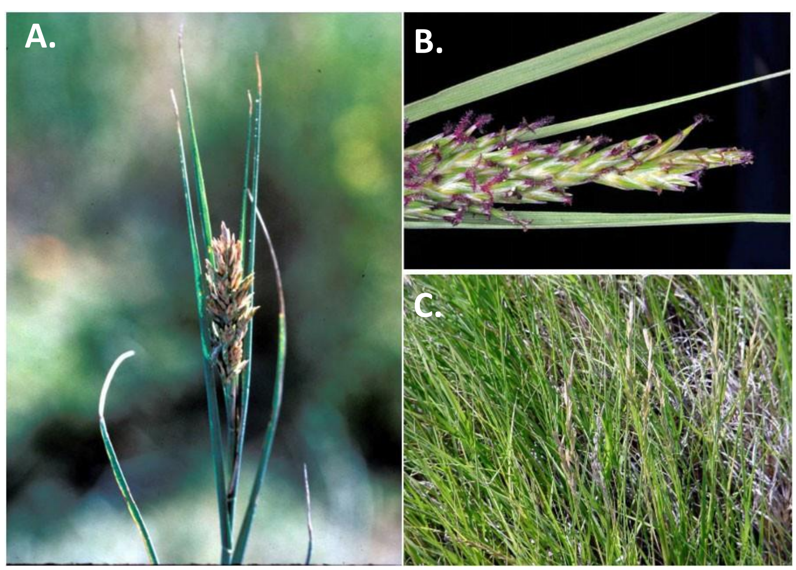


Photo credits: A. Fred Weinmann B.Robert L. Carr and C. Richard Old

Redtop *(Agrostis gigantea)*

A. Plant: Perennial, coarse dense turf, stems are slender, erect

B. Leaves: Sheathes open, narrow, sharp, flat or folded

C. Flowers: Open pinnacle, pyramidal, reddish purple

Habitat: Disturbed sites, roadsides, edge of agricultural fields, dry fields

Photo credits: Fred Weinmann B. and C. Richard Old

References:

Giblin, D.E. & B.S. Legler (eds.). 2003+. WTU Image Collection Web Site: Vascular Plants, MacroFungi, & Lichenized Fungi of Washington State. University of Washington Herbarium. Accessed 09 Sep 2020. http://biology.burke.washington.edu/herbarium/imagecollection.php.

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