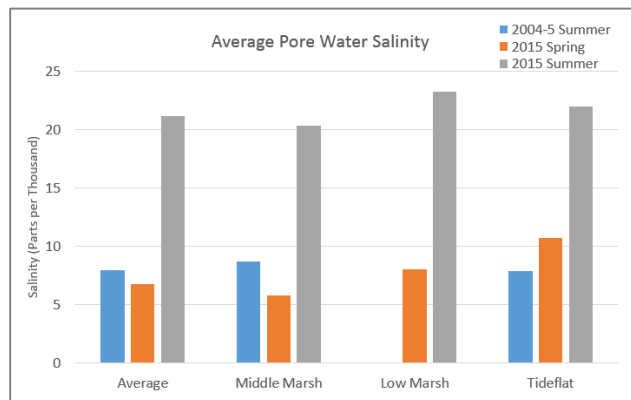


2015 Extreme Summer Salinity in the Stillaguamish Estuary

Monitoring Memo, Western Washington University
Prepared for The Nature Conservancy of Washington

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Importance of pore water salinity

Salinity is one of the primary drivers of plant species distribution and productivity in estuaries, along with inundation period (elevation) and sediment type. Salinity is a stressor for plants, and as a result the species diversity and productivity in tidal marshes generally declines as salinity increases. Salinity distribution in the estuary is also strongly affected by climate change impacts on sea level and river hydrology, and so is critical to understanding how and when estuaries will respond to climate change.

Salinity in the water column is easy to measure, but highly variable as the tide rises and falls each day, and as river flows vary according to precipitation patterns. Salinity of the soil (pore water salinity) is harder to measure, but is less variable than the overlying water. Pore water salinity can be higher or lower than surface water salinity because it responds to longer term patterns and is less sensitive to individual events like a rain storm or a spring tide. Since plant roots are in the soil and are the mechanism by which plants absorb water for photosynthesis, pore water salinity is more important than surface water salinity, in terms of understanding how tidal marshes will respond.

There is little in the published literature describing the salinity tolerance limits of the plant species common in Puget Sound estuaries. The best source is Hutchinson (1988) who summarized the available literature for most of the relevant species. For both *Schoenoplectus americanus* and *Bolboschoenus maritimus* he found a maximum field soil salinity of 15 ppt. He found that *S. americanus* germinates better at low salinities, though mature plants may tolerate occasional salinities as high as 20. At 15ppt there was a 62% reduction in growth of *S. americanus*. Similarly, Howard and Mendelssohn (1999) found that *S. americanus* biomass declined by 60% at 12ppt, compared to freshwater. A study at a warm temperate estuary in Portugal (Lillebo *et al.* 2003) found that *B. maritimus* (presumably *var. maritimus* which is a different variety than ours) occurs in areas with much higher summer salinity (>25ppt) values than other reported areas. The warmer winter temperatures allowed it to adapt by completing its annual growth cycle between January and May when salinities were 10-20ppt. They found that senescence began at about 15ppt and that sustained 20ppt brought complete senescence aboveground.

Table 1 shows the maximum field salinity identified by Hutchinson (1988) for the major species found in the Stillaguamish tidal marshes.

Table 1. Pore water salinity tolerance of dominant marsh species in the Stillaguamish estuary, as reported by Hutchinson 1988. Question marks are the author's. Species names have been updated to reflect recent changes.

Species	Max field salinity
<i>Agrostis stolonifera</i>	14
<i>Bolboschoenus maritimus</i>	15?
<i>Carex lyngbyei</i>	20
<i>Juncus balticus</i>	27
<i>Schoenoplectus americanus</i>	15
<i>Schoenoplectus tabernaemontani</i>	10
<i>Typha angustifolia</i>	18?
<i>Typha latifolia</i>	8

Climate change effects

In the context of climate change, sea level rise can increase the penetration of higher salinity water into the estuary. At present, the National Research Council projects that sea level will rise by about 24 inches (62 cm) for the Puget Sound area by 2100 (NRC 2012). This is likely a conservative estimate since our understanding of Greenland/Antarctica glacial dynamics is rapidly evolving, and since the NRC assumed positive vertical land motion of about 1mm/year which may be an overestimate for Puget Sound, particularly with the deep alluvial soils of estuaries.

Reductions in river flow can also increase salinity penetration, and the UW Climate Impact Group projects very strong declines in summer low flow. For an optimistic low carbon emissions scenario (RCP 4.5), they project a 30-40% decline in the 2-yr low flow by the 2050's. Summer flows may be particularly important for the estuary since it is the season of growth and reproduction.

Pore Water Salinity Monitoring

We sampled pore water salinities throughout the estuary during both spring and summer 2015. Our intent was to capture the anticipated extreme low flow event resulting from an anomalously warm winter. The year was a good analog for climate change effects because we received a normal amount of precipitation, but most of it fell in the mountains as rain rather than snow, leading to extremely low flows during the summer. The UW Climate Impacts Group projects that the conditions we experienced in 2015 will be the average condition in the 2050's (G. Mauger, pers. comm.)

For the months of July-August, which are the last two months of the estuary growing season for the dominant bulrush species, mean river flow in 2015 was the lowest in all 87 years of flow records from the oldest gauge in the Stillaguamish River (Figure 1). The average July-August flow is almost 700 cfs, but in 2015 flows remained below 300 cfs for 75 days between mid-June to late August. This duration of unbroken low flows was only exceeded in 1938 and tied in 1998, though the average flow in those years was higher than in 2015.

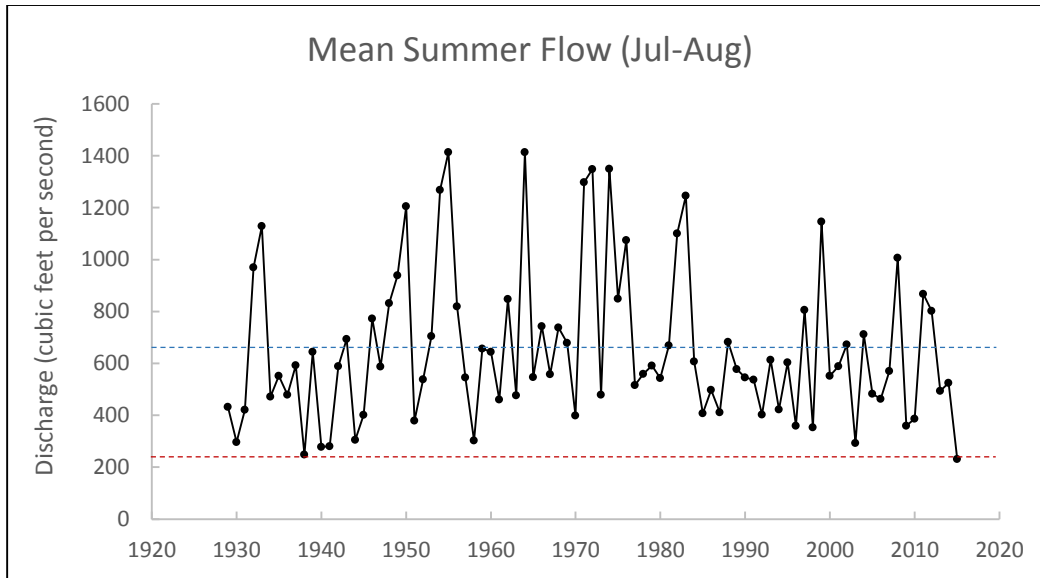


Figure 1. Mean annual summer flow (July and August) at the North Fork Stillaguamish gauge (USGS gauge number 12167000). The blue line is the average across the 87 year history. The red line is 2015. Annual data points are the mean of daily average flows for July-August.

In this report we summarize the pore water salinity data from 2015, and we compare vegetation height between 2014 and 2015. We don't have salinity data from 2014, but we can compare the average daily flows for July and August between the two years. In 2014, they were close to the long-term median values, in contrast to 2015 when the median flow was reached or exceeded on only 3 days (Figure 2). When pore water salinities were sampled in late August 2015, flows were about 163 cfs, a little less than 50% of the median value of about 350 cfs for that week.

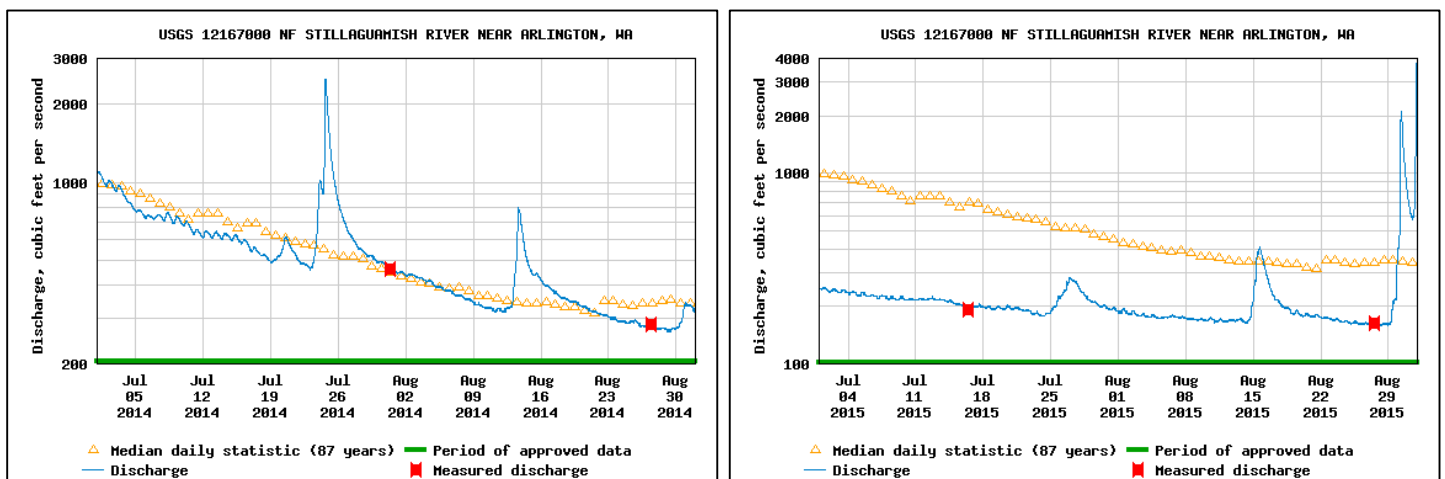


Figure 2. River flow for July and August, during 2014 (left) and 2015 (right) at the North Fork Stillaguamish gauge. 2014 was generally near the median daily value (yellow triangles), while 2015 only exceeded the median daily value on three days, briefly on 8/15, and again on the last two days of August. Graphs from the USGS gauge website (gauge number 12167000).

Field Methods

We collected pore water salinity measurements in the field using a refractometer. At each site, we dug a 10-20cm hole and allowed the pore water to accumulate until there was sufficient for testing. Occasionally we dug as deep as 30cm to obtain water. For recalcitrant pits that did not pool water, we extracted sediment and used a syringe (for coarser soil) or field press (for finer soil) to extract water. Before we began using compression to extract water from difficult holes, there were some samples from which we were not able to extract water and take readings. For all samples, we used glass filter papers and a syringe to separate suspended sediment from the water, prior to placing on the refractometer.

For spring data collection, we sampled while collecting sediment samples for laboratory analysis of PSD. Zones 1-5 (Figure 3) were sampled between late March and early May (3/24-5/4). We established three additional sampling zones to more completely characterize system-wide sediment characteristics, and zones 6-8 (Figure 3) were sampled between mid-May and late June (zone 6 on 6/6, zone 7 on 5/11, and zone 8 on 6/26). Within each study zone, we established a habitat transect parallel to the elevation gradient and described how vegetation and physical conditions varied across the gradient. In addition to collecting soil samples, we noted vegetation composition, measured soil penetrability, described soil surface conditions, and took both soil surface and perspective (habitat) photos.

Summer salinities and vegetation characteristics were collected August 24-31. During August we sampled only zones 1-5.

For the 2015 water year, beginning October 1, 2014, river flows were generally above the median statistic during winter (Figure 4), as would be expected when the snow:rain ratio skews towards rain. Similarly, this pattern leads to lower than median flows during the snow melt season. For four weeks during February and early March, flows dropped below the median, rose above median during the second half of March, then dropped below median until essentially the last two days of summer.

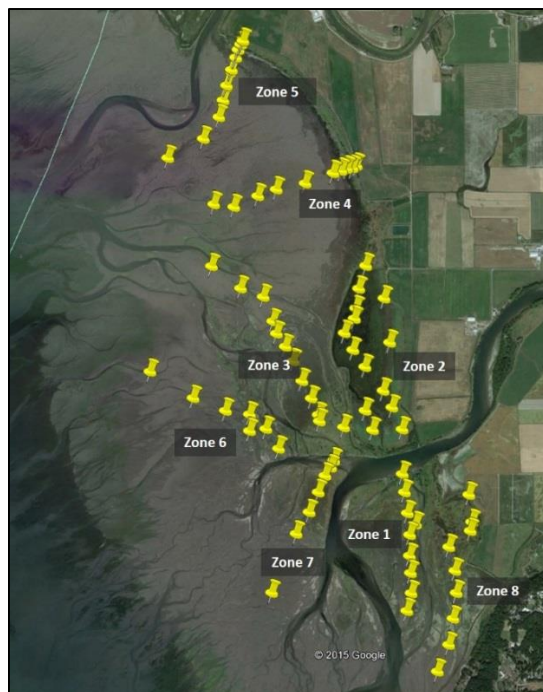


Figure 3. Sample locations in zones 1-8.

Spatial and Habitat Variability

In order to evaluate variability of salinity across the estuary, we summarized the data for each zone as well as for each habitat type within each zone. Habitat types included low, middle and high marsh, as well as tide flat. Low and middle marsh are regularly inundated for several hours on a daily basis. Low marsh is dominated by *S. americanus*. Middle marsh is dominated by mixed bulrush species, including *B. maritimus*, *S. americanus*, *S. tabernaemontani*, and *B. fluvialis*. High marsh occurs above and slightly below the MHHW mark, indicating that it is not inundated by the tide on a daily basis, but only by the higher tides of the lunar cycle. High marsh is usually dominated by graminoids such as *Carex lyngbyei*, *Juncus balticus*, *Agrostis stolonifera*, and *Distichlis spicata*. Many of the high marsh sites were dry (no pooling water after 10 minutes) when sampled in the spring, when we were not using the compression method to extract soil water. As a result of few data points, the summary tables and graphs presented below do not include high marsh. However the high marsh data is discussed in context.

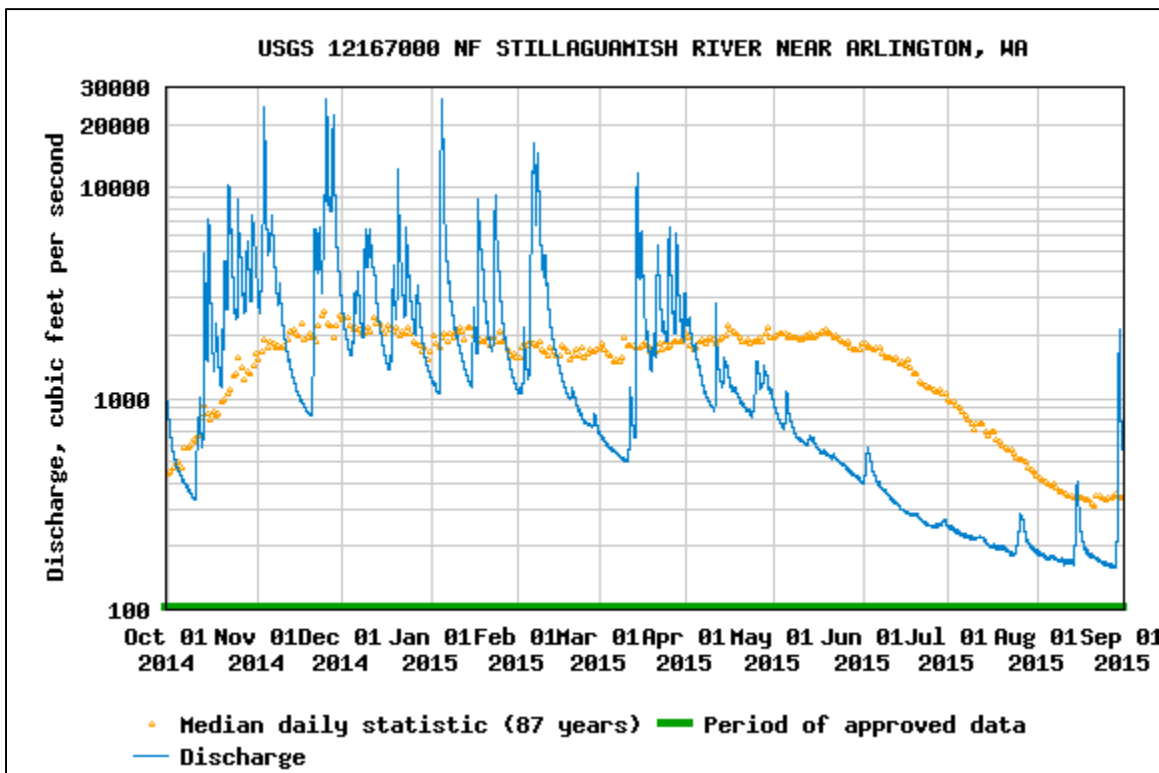


Figure 4. River flows during the 2015 water year, beginning on October 1, 2014.

Historic Data

Pore water salinity data was also collected by TNC during the first habitat characterization efforts in 2004-2005. Sample plots were selected with a stratified random approach, to characterize the major habitat types, which were Japanese eelgrass, tide flat, vegetated tide flat (less than 15% cover of *S. americanus*), low marsh, high marsh, diked-high, and diked-low. For the purposes of this report, we assigned the sample plots to one of our current 8 sampling zones, and based on the vegetation assigned

them to one of our current habitat types (high marsh, middle marsh, tideflat). For the 2004-5 sampling, low marsh was defined as any regularly (daily) flooded marsh. Currently we divide this zone into two habitat types, including “middle marsh” to separate the higher mixed-bulrush community which tends to have multiple species with taller and more robust stems, from “low marsh” which is dominated only by *S. americanus*. Since the historic designation did not make this distinction, we lumped all of the historic “low marsh” plots into our “middle marsh” category. Plant data exist for each historic plot, so it would be possible in the future to assign the historic plots to our new definitions. We lumped the historic categories “vegetated tide flat” with “tide flat” since a quick examination of data and photos suggested that the vegetated tide flat plots were mostly much less than 5% cover.

For the purposes of comparison with current data, we lumped the historic data from 2004 and 2005 into a single dataset. Many but not all of the plots were assessed in both years. 2004 data were collected in late July to early August (7/26-8/4). 2005 data were collected in two batches during mid-July (zones 1-3) and mid-August (zones 4 and 5). While most plots in zones 2 and 3 were collected in July, a few were collected a month later in August. However none of them exceeded the highest salinities recorded for their zones during July, so we chose not to remove them from the dataset.

Results

Across the system, between spring and summer 2015 we found that salinity generally tripled in marsh habitats and doubled in tide flats (Table 2, Figure 5). We found the 2004-5 summer data was nearly the same as the spring 2015 data, with slightly higher values in marsh habitat during summer 2004-5 compared to spring 2015, while tide flat values were slightly lower in summer 2004-5 than in spring 2015.

Table 2. Average pore water salinity values across the estuary.

	2004-5 Summer	2015 Spring	2015 Summer
Average	8	7	21
Middle Marsh	9	6	20
Low Marsh	NA	8	23
Tideflat	8	11	22

Average salinity across the estuary during summer 2015 exceeded 20 ppt (Table 2, Figure 5) which was well above the literature-reported values for the maximum tolerance level for bulrush species (Table 1). Indeed, Lillebo et al. (2003) found complete senescence of *B. maritimus* at 20 ppt, and multiple authors have found large reductions in biomass production beginning at 12-15 ppt. This is one of the most common and productive plant species in the Stillaguamish estuary, and thus is key to supporting the detritus-based foodweb of the estuary.

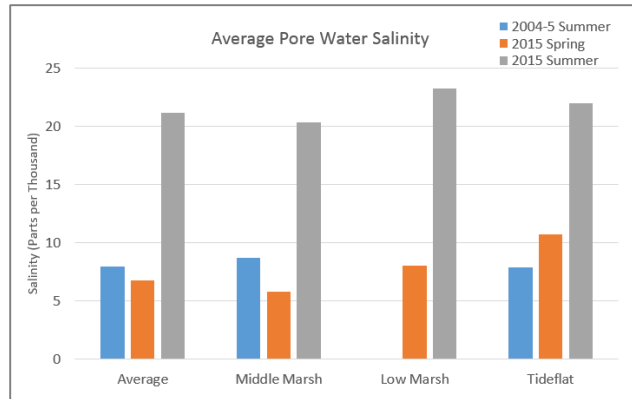


Figure 5. Average seasonal pore water salinity across the Stillaguamish estuary.

When we examine salinity differences among the five study zones, we see as expected that soil salinities are lower near the mouth of Hatt Slough and increase with distance away from Hatt Slough (Table 3). The observation that Zone 5 tends to have higher salinities than Zone 4 is an indicator that there is little river flow coming via the Old Stilly channel to South Pass. This is supported by the observation that the water level logger at South Pass becomes encrusted with barnacles while the other loggers in zones 1-4 do not.

Table 3. Pore water salinity values in the five study zones of the Stillaguamish estuary.

	Zone 1			Zone 2			Zone 3			Zone 4			Zone 5		
	2004-5 Summer	2015 Spring	2015 Summer	2004-5 Summer	2015 Spring	2015 Summer	2004-5 Summer	2015 Spring	2015 Summer	2004-5 Summer	2015 Spring	2015 Summer	2004-5 Summer	2015 Spring	2015 Summer
Average	4	4	18	9	7	21	6	4	23	10	8	22	11	10	23
Middle Marsh	3	2	16	11	7	20	7	4	23	10	7	20	13	9	23
Low Marsh		6	21					7	25		10	22		10	25
Tideflat	5	10	22		11	22	7		20	9	12	23	11	11	23

Zone 1

In Zone 1, we found that marshes were near 5 ppt in summer 2004-5 and spring 2015, but ranged 16-21 in summer 2015 (Table 3, Figure 6). The middle marsh here had the lowest pore water salinity (16 ppt) of all low and middle marsh sites in summer 2015. Even this lowest value exceeded the “maximum field salinity” tolerance reported (Hutchinson 1988) for bulrush species (15 ppt, Table 1). Tideflat salinity was always higher than marsh salinity, though not substantially. It was twice as high in spring 2015 (10 ppt) than 2004-5 summer (5 ppt), and more than doubled to 22ppt in summer 2015.

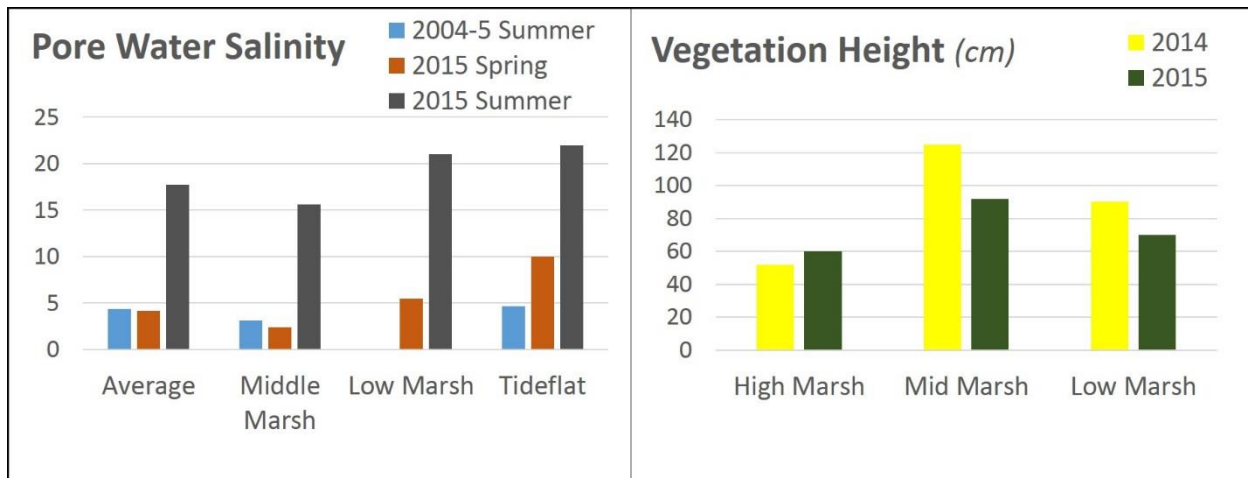


Figure 6. Zone 1 pore water salinity and vegetation height.

To understand the potential effect of salinity on vegetation, we can compare vegetation height between 2014, when river flows were near the median values, and 2015 when flows were nearly 50% of the median. We did not conduct experiments to demonstrate causative effects, so we can't say for certain that the vegetation differences were due to salinity, but it illustrates potential effects that merit further study. In 2015 middle marsh vegetation height was about 30% lower than in 2014, and low marsh was about 20% lower (Figure 6).

Zone 2

In zone 2, the restoration zone, we found that salinity was slightly higher in 2004-5 summer than 2015 spring, and that 2015 summer values exceeded 20 ppt in the marsh, almost three times higher than 2015 spring values (Table 3, Figure 7). Vegetation height in Zone 2 was almost 60% lower in 2015 than in 2014 (Figure 7). Tideflat salinities were always higher than marsh salinities, and they doubled between spring to summer 2015.

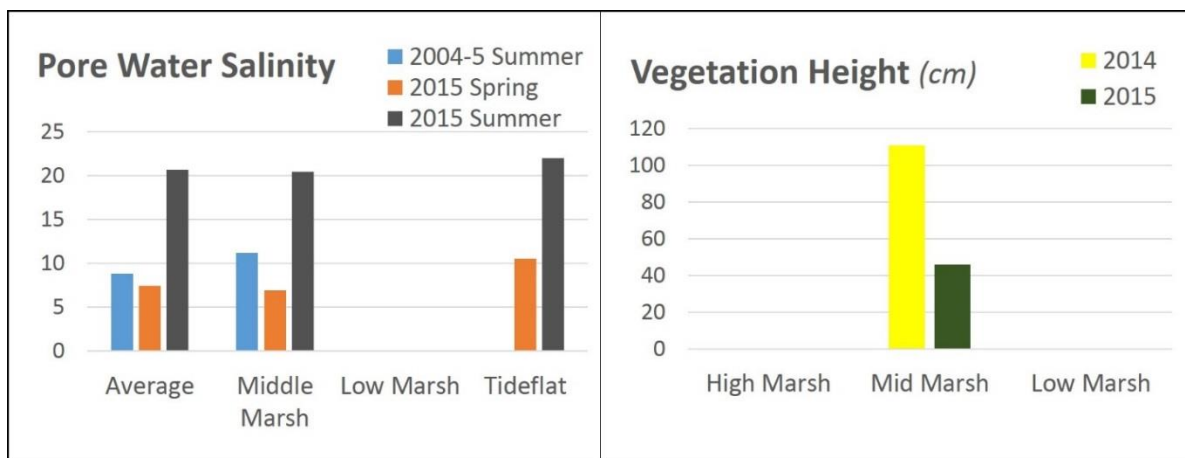


Figure 7. Zone 2 (restoration zone) pore water salinity and vegetation height.

Zone 3

Like Zone 1, Zone 3 is near the mouth of Hatt Slough, though it is surrounded by two distributaries that are much smaller than the channels that surround Zone 1. We found that Zone 3 spring 2015 salinities were similar to Zone 1 (4 ppt), and that 2004-5 summer salinities were not much higher (6 ppt). However summer 2015 marsh salinities were almost six times higher (23-25 ppt) than in spring (Table 3, Figure 8), and were 5 ppt higher in zone 3 than in zone 1. Vegetation was about 30% lower in height in middle marsh in 2015 compared to 2014 (Figure 8). For low marsh, the vegetation was about 40% shorter.

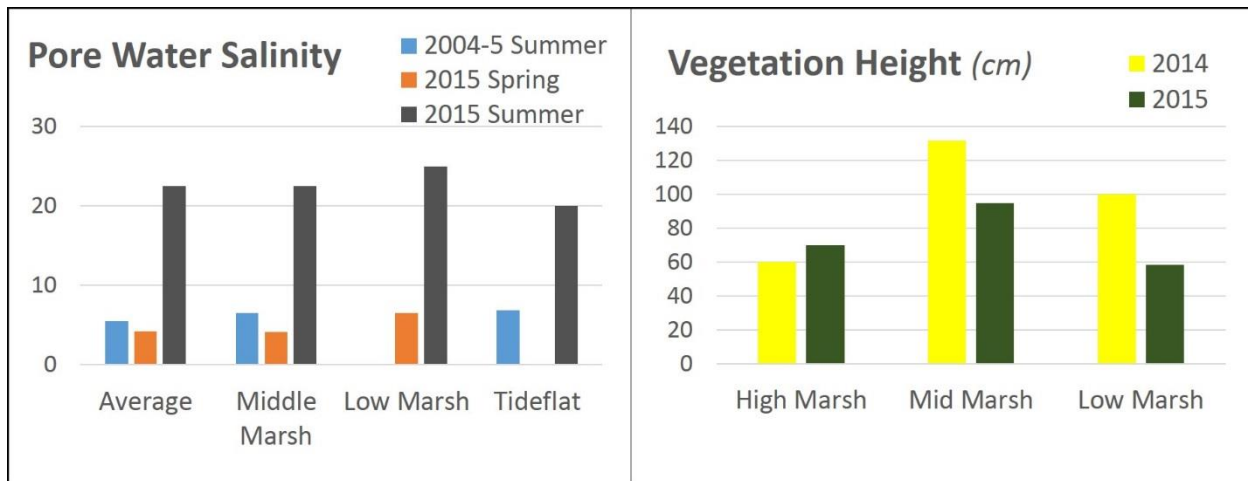


Figure 8. Zone 3 pore water salinities and vegetation height.

Zone 4

Zone 4 is the mid-delta region, farthest from distributaries, with the least tidal channel network development. 2015 spring marsh salinity (7 ppt) was lower than summer 2004-5 (10 ppt), while summer 2015 salinity in the middle marsh was twice as high as the 2004-5 summer value (Table 3, Figure 9). Low marsh salinity approximately doubled from spring to summer 2015, reaching a high of 22 ppt. Tideflat salinity similarly nearly doubled, reaching a high of 23 ppt. Vegetation height in the middle marsh declined by about 20% between 2014 and 2015, and low marsh height declined by about 45%.

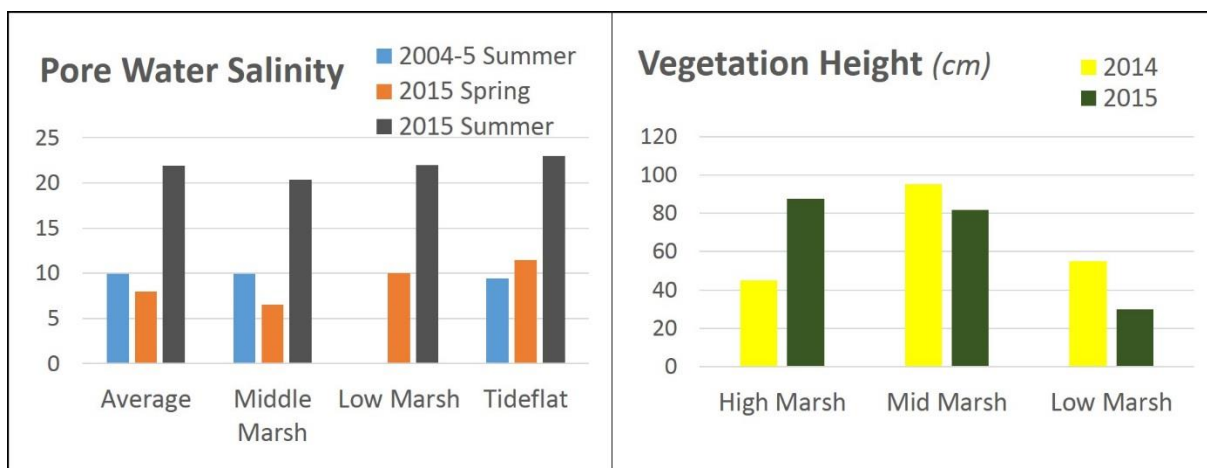


Figure 9. Zone 4 pore water salinities and vegetation height.

Zone 5 generally had the highest pore water salinities in all seasons (Table 3, Figure 10). Marsh salinity was slightly lower in spring 2015 than in summer 2004-5, and salinity more than doubled between spring and summer 2015, reaching a high of 25 ppt. The latter was in low marsh and was the highest value ever measured in the estuary. Vegetation height in middle marsh declined by more than 35% between 2014 and 2015, and low marsh declined by more than 60%.

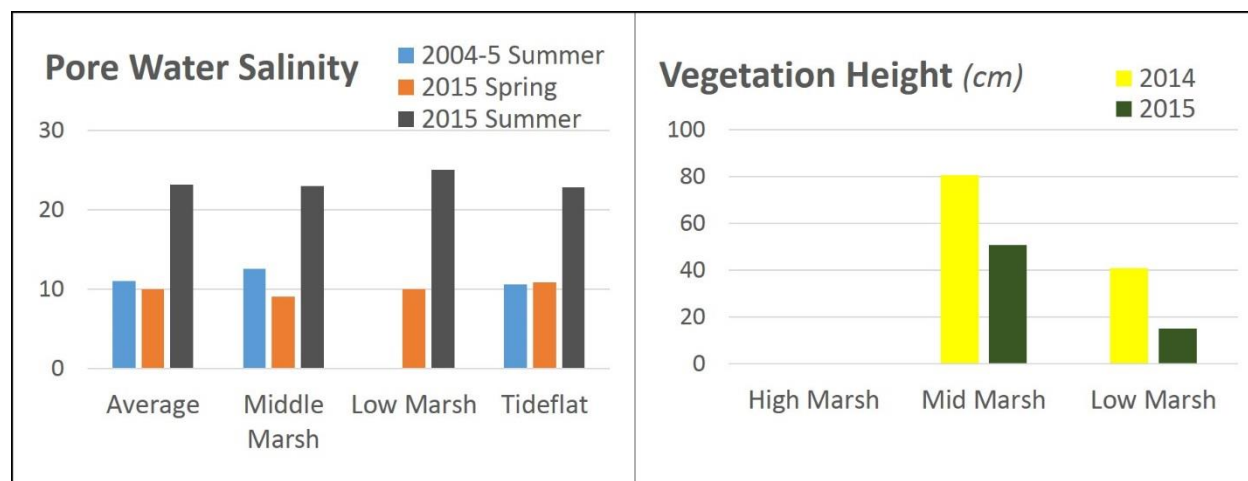


Figure 10. Zone 5 pore water salinities and vegetation height.

Zones 6-8

We sampled pore water salinity in zones 6-8 (see Figure 3 for locations) in late spring, between mid May and late June. These zones are all clustered near the mouth of Hatt Slough and so are expected to be similar to zones 1 and 3. The sample dates were later than for zones 1-5, so the extra zones were not included in the summary data analysis for spring 2015. Flows fell below the median statistic during April (Figure 4) and by May, pore water salinities may have begun to diverge from those characteristic of median flows. We found that all habitats in zones 6-8 had higher pore water salinities than found in zones 1 and 3 which were sampled in early May and early April respectively. Middle marsh salinity in zone 8 was 8 ppt, compared to 2 ppt in zone 1. Low marsh salinities in zones 6 and 8 were 14-15 ppt, compared to 6 in zone 1. Tideflat salinities were 14-18 ppt in zones 6-8, compared with 10 in zone 1.

However, it is interesting to note that this same pattern of higher salinities in zones 6-8 compared to zone 1, was also evident in the data from summer 2004-5 (Table 4).

Table 4. Pore water salinities during summer 2004-2005

	Summer 2004-5							
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Average	4	9	6	10	11	6	12	6
High Marsh	5	6	2	12			12	5
Mid-Low Marsh	3	11	7	10	13			6
Tideflat	5		7	9	11	6	12	8

General spatial patterns in pore water salinity

Effect of elevation

In spring 2015 pore water salinity was inversely related to elevation for habitat types inundated on a daily basis. Salinity was generally highest in the tidelflat, lower in low marsh, and lowest in middle marsh. However in summer 2004-5 there was little difference in salinity across this elevation gradient (Table 4), with tidelflats sometimes being slightly lower salinity than marsh. In summer 2015 regularly inundated marsh and tidelflats were similar in salinity, ranging from 20-25 ppt in all zones with the exception of middle marsh in zone 1 (16 ppt). As a result of these differing trends in each sample period, it seems likely that elevational differences in pore water salinity are variable across seasons or flow patterns, and that during summer there may be no difference between tidelflat and marsh.

We had few pore water salinity values for high marsh in 2015, which is why high marsh is missing from table 3. Because of this, we can't make any general statements about high marsh. However in zones 3-5 and 8, the few high marsh samples we collected in spring 2015 did follow the same general pattern described above for the spring, of having lower salinities than the lower elevation wetlands. High marsh salinities were 0 ppt in zone 3 (n=1), 3.5 ppt in zone 4 (n=2), 6 ppt in zone 5 (n=1), and 7 ppt in zone 8 (n=1, sampled late June). The only other high marsh sample collected in 2015 was in zone 7 (20 ppt) and it was an anomaly in that it was the highest pore water salinity recorded in the entire estuary during spring 2015 sampling. Not only was it anomalous for being in the high marsh, but it was also anomalous because it was in zone 7, adjacent to Hatt Slough and near the high marsh sample for zone 3, which had a value of 0 ppt, the only zero recorded in the entire estuary. Zone 7 had much more coarse soils than all the other zones and it is possible that the coarse sandy soils allowed salinity to penetrate farther inland in the groundwater than occurred in other zones.

Interestingly, those two extremes for zones 3 and 7 high marsh also appeared in the summer 2004-2005 sampling. The 2004-5 sampling successfully collected salinity readings from most of their high marsh plots (Table 4). Zone 3 high marsh had the lowest average salinity (2 ppt) in the entire estuary for that sample season, as it did in spring 2015. Zone 7 high marsh (12 ppt) tied with zone 4 for the highest average salinity in high marsh in summer 2004-5. In the entire estuary the only other places with salinity as high as 12-13 ppt were zone 5 mid-low marsh and zone 7 tidelflat. These high values in zone 7 summer 2004-5 may support the idea that zone 7 has physically and chemically different soil than adjacent marsh islands. These differences may result from the fate of sediment during flood flows which is likely the time when coarser sediments are moved into the estuary. Zone 7 would be positioned in the middle of the thalweg during a large flood.

Effect of landscape position

In general pore water salinity in natural reference marshes (zones 1, 3-5) increases from south to north, as distance from the mouth of Hatt Slough increases (Table 3). This pattern held true in summer 2004-5 and spring 2015, but not in summer 2015 when the differences among zones were negligible. All regularly inundated habitat salinities in summer 2015 were between 20-25 ppt except for zone 1 middle marsh (16 ppt). Zone 5 generally had the highest salinities of all zones, even in summer 2015. The hydro logger in zone 5 records higher surface water salinity, and it is the only logger station that becomes encrusted with barnacles. As a result, it is clear that very little fresh river water is conveyed via South Pass, from either the Old Stilly channel or from the South Fork of the Skagit. Zones 1-5 occur on a spectrum from low to high salinity.

Zone 3 middle and low marsh were slightly more salty on average than zone 1 during all sample periods. However, the difference was greater during summer 2015, with middle marsh salinity higher by 7 ppt in zone 3. Zone 3 is surrounded by two small distributaries while zone 1 abuts the largest distributary, so it is not surprising to see zone 3 salinities rise faster in summer than zone 1.

Interestingly, when we include the data for the new zones 6-8, the salinity patterns around the mouth of Hatt Slough become more complex. As indicated earlier, we had few salinity readings in zone 7 in 2015, with only a single reading in each of high marsh, middle marsh and tideflat habitats. Part of the reason for the few readings was the substantially coarser substrate which apparently allowed groundwater to drain more quickly (we were not prepared with a field press to extract pore water). However the high marsh (20 ppt) and tideflat (18 ppt) readings were both the highest salinity readings for their respective habitat types, even higher than zone 5. The fact that the summer 2004-5 data also show zone 7 as having salinity as high as zone 5, suggests that the few recordings in 2015 for zone 7 were not anomalous for that zone, and lends credence to there being a physical explanation, such as a difference in substrate particle size or groundwater dynamics. Zones 6 and 8 both had substantially higher salinities than zones 1 and 3 in spring 2015, though this is likely driven by being sampled in June, one to two months later, and after the point that flows had already dropped below 50% of the median. In the summer 2004-5 data, zones 6 and 8 both had slightly higher salinity than zone 1, and were similar to zone 3 (Table 3, Figure 11). Therefore, in general at the mouth of Hatt Slough, it appears that zone 1 consistently has the lowest salinities of all zones, zones 3, 6, and 8 have slightly higher salinities, and zone 7 has substantially higher salinities than the other southern zones. The restoration zone 2 has salinities that are less than zone 7 but higher than the other zones near Hatt Slough (Figure 11).



Figure 11. Map of salinity patterns in summer 2004-5. This general pattern of increasing salinity from south to north, appears to be typical. In contrast to the general trend, zone 7 consistently has higher pore water salinity than other southern zones, possibly due to substantially coarser soils.

Zone 2 was still diked in summer 2004-5. It had higher salinity than zones 1 and 3, and was in the same range as zones 4 and 5 (9-11 ppt). At the time we attributed this to the fact that it was not connected to

the flushing of river or tide system, and so seasonal evaporation in summer could have concentrated salts in the soils. The area had two general habitat types called “diked wetland” and “diked upland”. The wetland was dominated by *B. maritimus* and *B. fluviatilis* (the latter was not recognized at the time, but is currently present, and there remain old, undecayed stem stubs from pre-restoration whose large diameters clearly represent *B. fluviatilis*). The “upland” habitat was grassland dominated by *Agrostis spp.* and *Agropyron repens*, a weedy European grass. It is represented in table 4 in the “high marsh” row.

In spring 2015, salinity in zone 2 was still most similar to zones 4 and 5 (7-8 ppt), rather than zones 1 and 3. Despite being next to Hatt Slough, zone 2 is not directly connected to it and is only bordered on one side by a small distributary. In addition it is subsided compared to all the reference marshes, it has different soils (smaller particle size and greater penetrability), and it is more gently sloped which increases drainage time, increasing the effective inundation period. These factors may contribute to its salinity regime being more similar to the northern than the southern marshes.

Effects of salinity on vegetation

The extremely high salinities found in summer 2015 were accompanied by substantially shorter vegetation in all middle and low marsh areas of the estuary (Table 5). Even in the marsh with the lowest summer salinity (zone 1 middle marsh, 16 ppt), vegetation height declined by more than 25%. The salinity for this zone slightly exceeded the maximum field salinity tolerance (15 ppt) described by Hutchinson 1988 (Table 1) for the most salt tolerant bulrushes (*S. americanus* and *B. maritimus*). On average across the estuary, middle marsh declined by 34% and low marsh by 43%. Interestingly, high marsh increased in height, particularly in zone 4. Further assessment of the high marsh data is necessary to confirm that this difference is real. Graminoid species are more prone to wind or wave flattening by late summer than are the stiff-stemmed bulrushes, so differences in high may be related to other factors.

Table 5. Percent change in vegetation height between summers, 2014 and 2015.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
High Marsh	17		17	108		47
Middle Marsh	-27	-56	-40	-15	-34	-34
Low Marsh	-20		-41	-44	-67	-43

We did not assess changes in stem density, root biomass or other measures of total biomass, but the declines of height are in line with literature observations that bulrush species decrease in biomass by about 60% when salinity reaches 12-15 ppt (Hutchinson 1988, Howard and Mendelssohn 1999).

Interestingly, zone 4 middle marsh declined less than middle marsh in other zones, and zone 5 middle marsh did not decline quite as much as zone 3 despite having similar summer salinities. This pattern is likely explained by differences in species composition. In zones 1 and 3, middle marsh includes substantial cover of *S. tabernaemontani*, a tall bulrush with a lower salinity tolerance of 10 ppt (Table 1). It may have declined the most, in terms of height, affecting the southern zones’ average marsh height more strongly. In contrast, zone 4 middle marsh has no *S. tabernaemontani* but does have a large area of *B. fluviatilis*. There is no published record of salinity tolerance for *B. fluviatilis* (river bulrush) but we had assumed that it would be less tolerant of salinity than its closest cousin *B. maritimus* (seacoast bulrush). However, the two plots dominated by *B. fluviatilis* changed little in height between years, in contrast to *B. maritimus* plots which declined substantially. This could be due, in part, to the small

sample size of *B. fluviatilis* plots, however, anecdotally the broader areas dominated by *B. fluviatilis* did in fact appear to be less affected by the high salinities. In late August it was still very green, only beginning to senesce at leaf tips, while *B. maritimus* had completely senesced above ground in virtually all locations. Zone 5 middle marsh had similar species composition as zone 4, but its higher salinities were enough to depress the heights almost to the same extent as middle marsh in zone 3.

Low marsh, which is dominated only by *S. americanus*, declined in height uniformly from south to north, with the least decline (20%) in zone 1 and the greatest decline in zone 5 (67%). Low marsh salinity was very high in all zones (20-25 ppt) in August, so the spectrum of decline in height may be related to the proportion of the growing season that experienced high salinity, with southern zones reaching a critical threshold later in the season. Zone 5 may be near the salinity threshold in normal years. In summer 2004-5, the average salinity for the combined low-middle marshes was 13 ppt, close to the 15 ppt threshold suggested by Hutchinson 1988. In spring 2015, zone 5 low marsh had a salinity of 10 ppt, in contrast to 6 ppt in zone 1. All of which supports the idea that zone 5 likely passed the salinity threshold considerably earlier in the growing season than more southerly zones, accounting for its 67% decline in low marsh height.

We did not measure plant reproductive parameters, but in summer 2015 very few low or middle marsh areas had bulrush species that had flowered or set seed. Most years there is abundant seed set in most locations. Since we had identified the presence of *B. fluviatilis* during 2014, we attempted to collect seeds across the estuary in 2015, to help us with discriminating between *B. maritimus* and *B. fluviatilis*. However the only places we could reliably find *B. maritimus* seed was at the highest marsh elevations in the zones 1 and 2.

Zone 2 (Restoration Area) Vegetation

Zone 2, the restoration zone, is dominated entirely by middle marsh vegetation, despite having an extensive area within the elevation range of low marsh. The reason has to do with the pre-restoration legacy of a non-tidal wetland that was dominated by *B. maritimus* and *B. fluviatilis*. Virtually no *S. americanus* has established within the site, likely due to the very fine particle size of the soil. *S. americanus* appears to favor coarser soils. During summer 2015, vegetation height decreased by an average 56% in zone 2, the greatest middle marsh decrease in the entire estuary. This can be explained by the fact that much of the area vegetated by *B. maritimus* was at elevations lower than it occurs in the reference marshes, suggesting that it was already stressed before the extremely high salinity of summer 2015. Furthermore, a stem-boring moth attacked the restoration area in June 2015, infesting 75-100% of stems in the lower elevations (Fuller *et al.* 2015). The moth attack may have been facilitated by a marsh that was already under inundation stress and beginning to experience the stress of extreme salinities by June. Figure 12 shows the decline in vegetation cover in zone 2, from 2014 to 2015. In the area outlined in white in the 2015 aerial, most of the plants were dead by the end of June. These areas supported *B. maritimus* at elevations lower than where the species is found in reference marshes. We do not anticipate that the marsh will recover in 2016 in these locations. Low soil particle size suggests that *S. americanus* is unlikely to establish in significant densities, so we expect this area to remain largely bare until elevations or soil particle size change substantially.

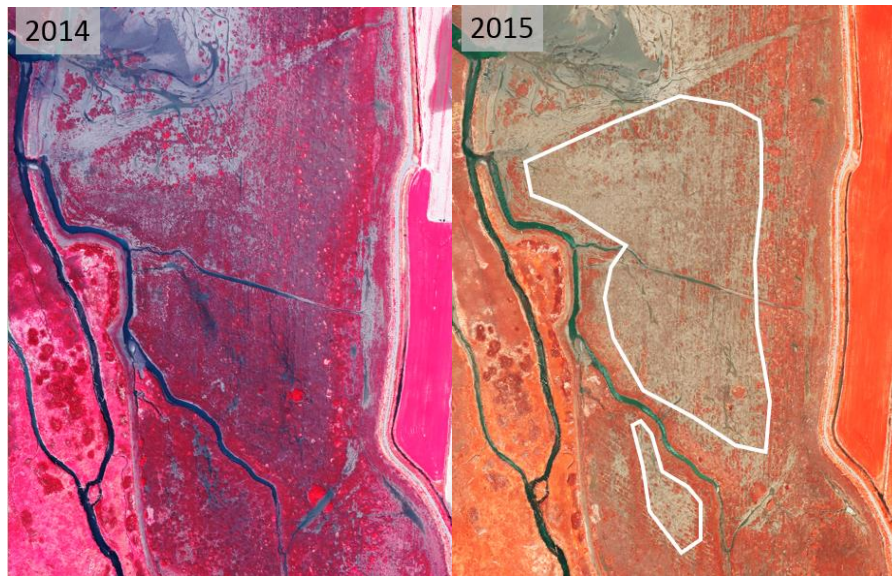


Figure 12. Infrared imagery showing the decline in vegetation cover (areas outlined in white) in July 2015 in the restoration zone, resulting from the insect outbreak. By August all plants were dead in the outlined area.

To illustrate the differences in vegetation in the restoration area between summer 2014 (normal flows) and summer 2015 (moth attack and extreme low flows), Figure 13 shows paired photos of the same plots. Near the southern end of the restoration area, plot 21006 is in the highest elevation area and is closest to the normal elevation at which *B. maritimus* is found in the reference marshes. In the paired photos, the vegetation appears similar in height and the plants are in full bloom in both photos. This is true even though the 2014 photo was taken about one month later, in mid-July, compared to the 2015 photo which was taken in mid-June. The black arrows in the photos point to the same spot on the horizon in both photos, to allow for direct comparison. Subsequent photo pairs are for plots farther north along the vegetation transect, heading towards the northern breach site, and at successively lower elevation. Each plot is 20m apart, so the approximate distance between photo pairs can be estimated by counting the number of plots separating the photos and multiplying by 20m. Subsequent plots clearly show the rapid decline in plant height and density as elevation decreases.

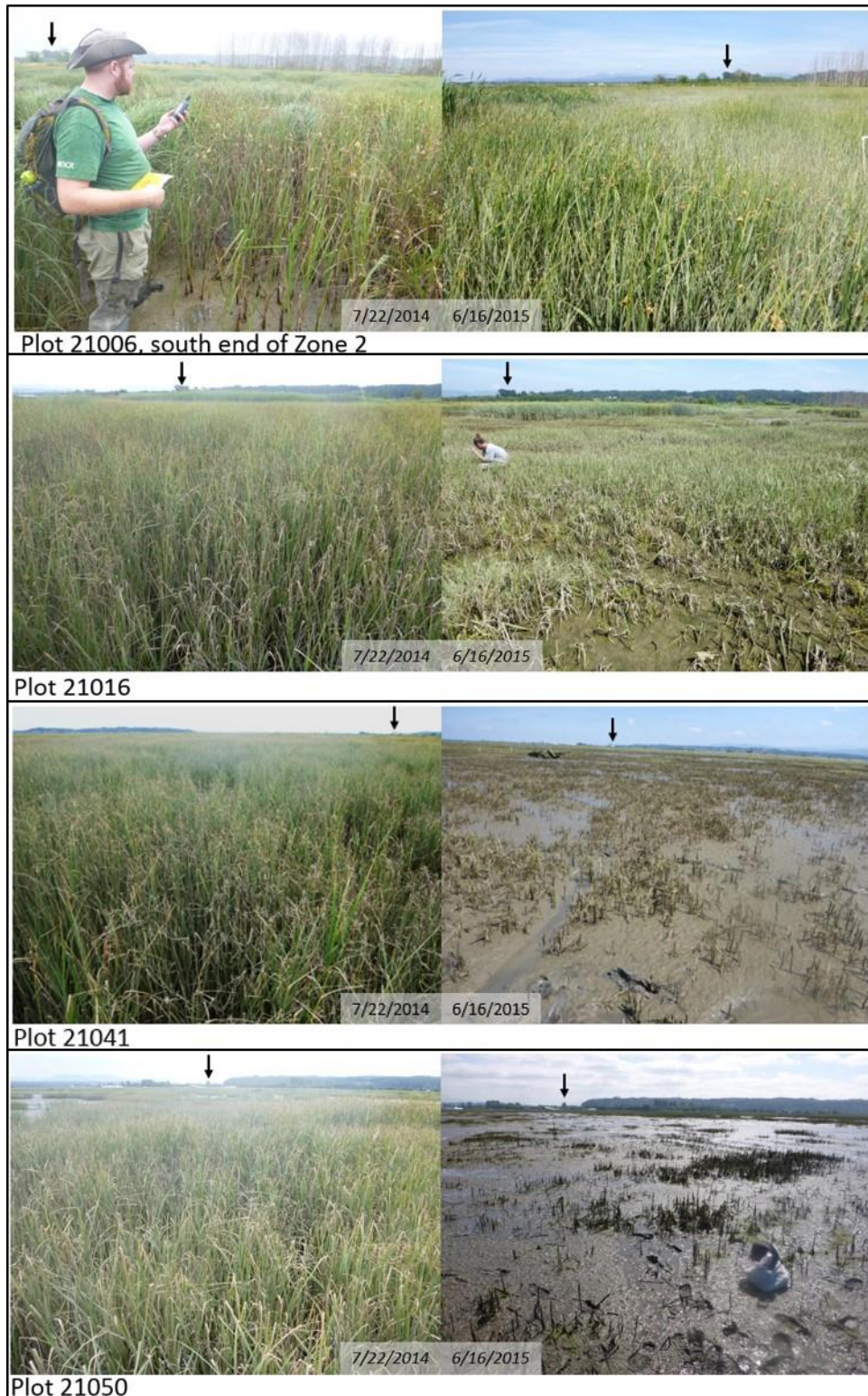


Figure 13. Zone 2 (restoration area) plot comparisons between 2014 and 2015. The paired photos begin at plot 21006, at the highest marsh elevations to the south near Hatt Slough. Vegetation at this plot is similar between years. The subsequent plots are at successively lower elevations and illustrate the rapid decline in plant height and density as elevation decreases. To assist with orientation, the black arrows indicate the same location on the horizon in each photo.

Conclusions

Pore water salinity in summer 2015 was sufficiently high throughout the estuary to affect plant growth, reproduction and the production of biomass to fuel the broader food web. The fact that salinities were higher throughout the entire estuary than published maximum tolerances for the dominant bulrush species suggests potential vulnerabilities for the estuary in the context of climate change. Precipitation and river flow patterns in 2015 was similar to those projected to be average by 2050 (G. Mauger, pers. comm.) As a result there could be quite substantial vegetation changes in response to changes in river flow over the next few decades.

However ecosystems are complex and there are various interactions that could affect the outcome. For example, Lillebo *et al.* 2003 found that *B. maritimus* could survive in the warmer waters of Portugal where summer salinity exceeded 25 ppt because the warmer temperatures allowed it to complete its annual growth and reproductive cycle during late winter and early spring, before salinity reached 20 ppt. At the Stillaguamish, the *B. maritimus* growing season is also about 5 months long, but occurs April-August. Increasing salinity during the summer growing season would curtail bulrush, unless warming temperatures allow the growing season to shift earlier in the year. It would be worthwhile to investigate the projections for monthly changes in temperature and identify the temperatures associated with the current life history of *B. maritimus*. At Port Susan Bay, citizen science could help to record the annual phenology of dominant plant species and help us track how the marsh changes over coming decades.

However, other research has found that the interaction of salinity changes with other stressors such as flooding (e.g. sea level rise) or grazers could be sufficient to push marshes over key thresholds. For example, Gough and Grace (1998) found that, when combined with flooding and salinity changes, herbivore pressure further reduced species richness and biomass. Similarly, Baldwin and Mendelssohn (1998) found that disturbance, in combination with rising sea level, can catalyze rapid shifts in vegetation structure and accelerated wetland loss.

Different plant species may be differently susceptible to salinity changes. For example, *B. fluvialis* appeared surprisingly more robust in the face of high salinity than *B. maritimus*. It has a substantially more narrow elevation range, but management efforts could work to target that range, for example by modifying elevations within restoration sites to favor *B. fluvialis*. It is found in all of the five study zones and along South Pass.

If the extreme 2015 river flow and salinity patterns become average conditions over the next few decades, this has implications for restoration and management decisions now. For this reason, it would be important to set up a monitoring program now that is capable of tracking how quickly the marsh recovers from last year, and to track future salinity dynamics and plant responses. The study we did this past year was very small but provides clear indication of important dynamics that may substantially affect estuary productivity and support of critical species over the next few decades.

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