PHRAGMITES INVASION DRIVERS IN FARMINGTON BAY WETLANDS, GREAT SALT LAKE, UTAH

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EXECUTIVE SUMMARY

Phragmites australis has expanded in an alarming rate since our initial surveys conducted during 2004. We developed and measured various *Phragmites* condition metrics to determine whether differences occurring among the sites could be attributed to various environmental characteristics including nutrient enrichment. We selected six sites around Farmington Bay that were representative of different conditions including sites that were: down-gradient of effluent discharges, grazed for *Phragmites* control, down-gradient of tributaries and springs but also partially grazed and managed, and one control (not managed, not grazed, and not immediately down-gradient of an effluent discharge). The selected sites ranged from fresh water to saline, inundated most of the sampling period to mostly dry.

Many factors likely influence the extent and robustness of *Phragmites* around Farmington Bay. We found surface water nutrient and water quantity to be the most important factors influencing *Phragmites* condition around Farmington Bay, however we identified additional variables related to management of water and *Phragmites*, salinity relative to hydrology and post-Great Salt Lake flood dynamics, and sediment toxicity that give *Phragmites* a competitive edge over other wetland plants and invasion out onto mudflats. We found that elevated phosphates associated with surface water, moderate salinity and moderate sediment toxicity are important factors that correlated with the highest proportion (determined as percent cover) and greatest canopy height (as average maximum height). Other factors that contribute to *Phragmites* proportion and robust stature were water depth between zero and 20 cm, and flow rates up to 5 cm / sec, respectively. Cattle were effective when actively grazing, but without additional control mechanisms, sites filled in vigorously when cattle were not returned to the site the following year. These factors have important management implications for areas that use water and cattle (or mechanical mowing) as control agents of *Phragmites*.

While *Phragmites* likely established more readily at point sources as a result of elevated surface water phosphorus and / or persistent shallow water during early months of establishment though mid-summer or longer, it is no longer constrained to nor more robust at our discharge sites than other fresh to brackish locations around Farmington Bay. Future research and management should prioritize what can be done to minimize further loss of shorebird habitat related to continued expansion and invasion by *Phragmites* because it isn’t clear that reduced surface water phosphorus loading would make a difference when sediment phosphorus levels in Farmington Bay are naturally elevated and have been relatively unchanged through our recent human history. Far more relevant is the loss of saline moist and shallowly flooded wetlands that used to characterize Farmington Bay. These wetlands are highly important for producing macroinvertebrates that shorebirds and other waterbirds depend upon for forage and for providing nesting and loafing habitat where approaching predators can be seen due to an open, unvegetated setting. To date, tremendous efforts and resources have been dedicated to

research and control of *Phragmites* in wetlands of Great Salt Lake, with some areas showing significant control. While it is important to continue efforts to control it, our research shows a dire need to treat the advancing or leading edge of *Phragmites* so that the saline moist and shallowly flooded habitat that remains is conserved and protected for shorebirds and their aquatic food chain.

INTRODUCTION

Phragmites australis has expanded in an alarming rate since our initial surveys conducted during 2004. Prior to that time, Great Salt Lake flood waters saturated its fringing shores and adjacent uplands with hypersaline water during the 1980s; salts were deposited as flood waters receded, and several years of drought followed setting a pattern of many years of disturbance to the landscape. Concomitant with this disturbance and gradual leaching of salts from surface sediment was the arrival of an invasive genotype of this wetland plant. Non-native genotypes of *Phragmites* have become established in every mainland U.S. state within the last 200 years and are invading inland areas where it had not previously occurred, many of which are undisturbed (Saltonstall 2002).

We have documented expansion of *Phragmites* into and far beyond areas that were unvegetated saline mudflats of Farmington Bay (Miller and Hoven 2007; Hoven 2012; Hoven and Richards 2016). The fundamental question behind our 2015 and 2016 Farmington Bay *Phragmites* study was to determine whether nutrients in effluent discharges that drain into Farmington Bay are enhancing the distribution of monotypic stands of invasive *Phragmites* to the point where beneficial use pertaining to aquatic life (e.g., shorebirds and other waterbirds) habitat and forage are compromised. Our 2011 comparative study between a discharge influenced site (down-gradient of Central Davis Sewer District, CDSD) and non-discharge influenced site (Kays Creek) identified several plant metrics that may have indicated *Phragmites* sensitivity to nutrients, trace elements (metals), and salinity but because there was only one site visit, ecological interpretation relative to biological response was limited (Hoven 2012). During 2015, we expanded our efforts to include two sites down-gradient of effluent discharges, one site that was grazed for *Phragmites* control, one site that was down-gradient of tributaries and springs but also partially grazed and managed, and one site that served as a control (not managed, not grazed, and not immediately down-gradient of an effluent discharge). An effect of nutrients on the proportion of *Phragmites* was not indicated that year, however, the stature may have been affected (Hoven and Richards 2016). The 2015 results were preliminary and needed to be substantiated with a more robust data set. During 2016, an effort was made to develop additional metrics that could be important in explaining the extent and distribution of *Phragmites*. We also added a sixth site, down-gradient of the North Davis Sewer District discharge (NDSD), to include response that may be contributed to higher volume and flow of water. The NDSD site was part of the original 2004/2005 surveys, thus those preliminary data were included in this assessment. As salt is an integral component of the Great Salt Lake ecosystem, the level of salt influence at each site was treated as an effect.

METHODS

100 m transects were established perpendicular to water flow at the 2004/05 transect locations (Miller and Hoven 2007) and those established during 2015. At each site, the first transect was located at the point where the discharge, outflow or tributary began to sheetflow. The second transect was located (in most cases) approximately half the distance from origin of sheetflow and the extent of the *Phragmites*

distribution along the flow path of water towards the lake and perpendicular to flow. Assessments occurred within ten randomly located $1m^2$ quadrats (0.5 m x 2.0 m, placed perpendicular to the transect line) along each transect. One modification of transect placement that was made during 2015 and 2016 sampling was to place the transect from the edge of the main flow outward in a 90° direction, rather than bisecting the flow as originally designed in 2004, to capture any horizontal gradient in plant community response relative to exposure to the main discharge or flow.

Access to each transect and the transect distance was cut by hand with a machete, with one exception during 2016. At CDSD, we were transported by way of a Marsh Master, which was purchased by the District to cut a path through and chemically treat the *Phragmites* to re-establish water flow to Farmington Bay that was otherwise lost to evapotranspiration by *Phragmites* (Figure 1).

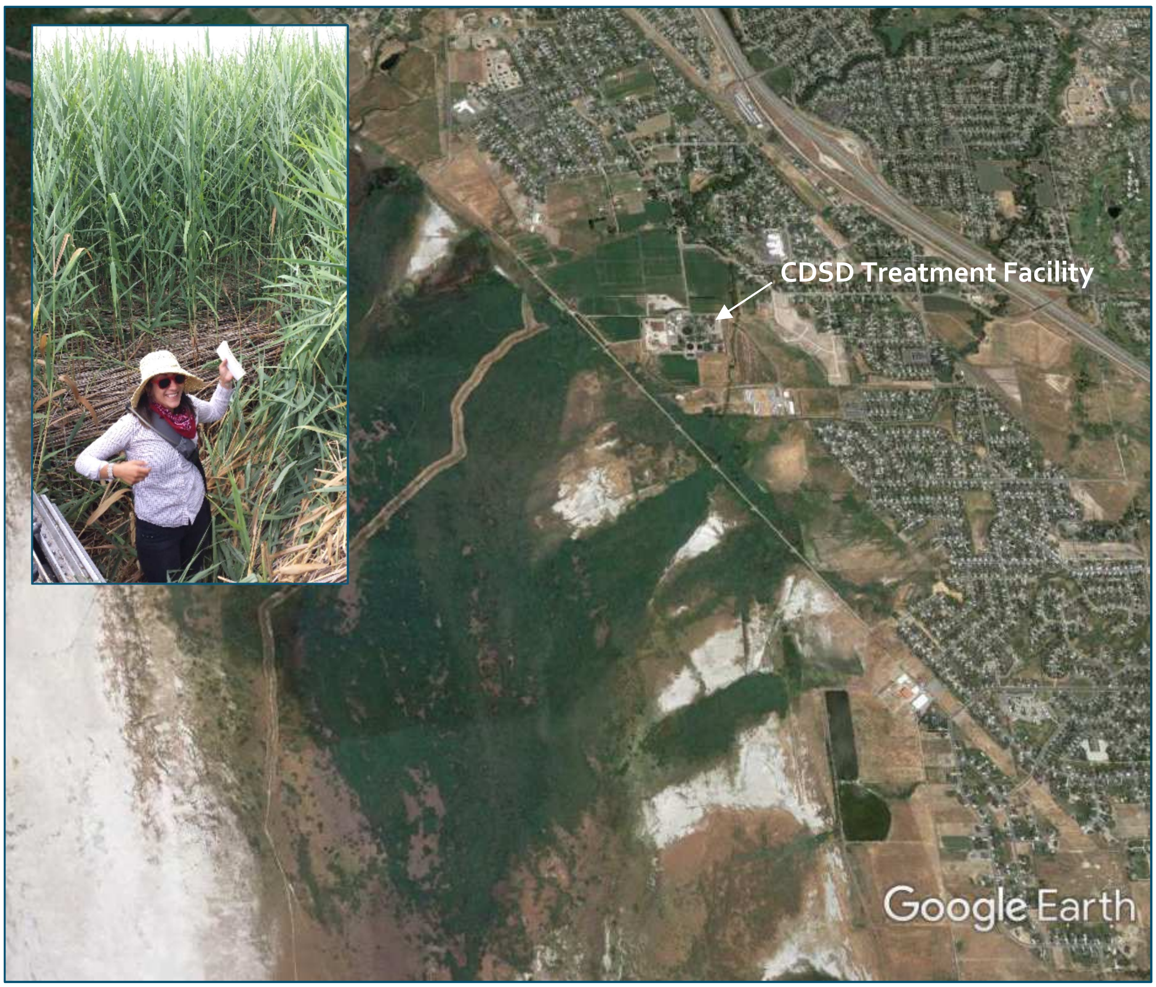

Figure 1. Field assistant standing next to chest-high track of Marsh Master during July 2016 in vicinity of transect at CDSD (inset). Note height of litter (tan horizontal stems), height of canopy, and density of live stems. Note path cut by Marsh Master from the CDSD discharge to remove obstruction of water flow by *Phragmites*. (Photo: H. Hoven; Google Earth image, July 2016).

A total of 6 sites were assessed (Figure 2). They were: north of the Farmington Bay Wildlife Management Area Turpin Unit (TU, grazed); Kays Creek (KC, partially grazed through 2016, periodically chemically treated (managed), and not discharge influenced at the first transect; non-grazed, not managed through 2016 and not discharge influenced at the second transect); Lake Front Duck Club (LF, non-grazed, not managed, not discharge influenced, serving as a control); NDSD, (ND, discharge influenced); CDSD (CD, discharge influenced); and the Northwest Oil Drain (OD, discharge influenced).

Figure 2. Six fringe wetland sites surrounding Farmington Bay, each with two transect locations: North Davis Sewer District (ND), Kays Creek (KC), Central Davis Sewer District (CD), Turpin Unit (TU), and the Northwest Oil Drain (OD). Google Earth image, June 2016.

All transects were located and established using a Garmin Colorado 400t GPS, being careful not to cut too wide of a path that would alter sunlight distribution through the canopy for subsequent assessments (Table 1).

Table 1 Latitude and longitude of transect initiation points located at six sites around Farmington Bay, 2015/2016

SITE	LATITUDE	LONGITUDE
ND1	41°4′49.09″N	112°7′29.54″W
ND2	41°4′38.46″N	112°8′4.48″W
KC1	41°1′49.16″N	112°0′48.97″W
KC2	41°1′31.25″N	112°1′19.57″W
CD1	41°0′0.67″N	111°57′33.52″W
CD2	41°59′45.90″N	111°57′47.95″W
TU1	40°55′32.79″N	111°58′36.32″W
TU2	40°55′41.78″N	112°58′43.55″W
OD1	40°54′5.98″N	112°1′29.54″W
OD2	40°54′28.34″N	112°2′16.73″W
LF1	40°52′56.91″N	112°2′6.69″W
LF2	40°52′58.52″N	112°2′5.51″W

Sites were visited during 3 to 4 consecutive monthly assessments during 2015 and 2016 to compare differences in the establishment and development of plant communities that could be attributed to different environmental effects including nutrients. Data from 2005 and 2011 that were collected from matching site locations and during the same months as that collected during 2015 and 2016 were included in our analyses. All of the down-gradient transect locations had to be re-located due to expansion of *Phragmites* since 2005. Additionally, some of the original transect locations were inaccessible due to the denseness of *Phragmites* (CDSD) or the hydrology had changed since 2005 (e.g., Kays Creek, Turpin Unit outflows); in both cases, transect locations were moved. Four of the 2015/16 sites that were part of the original set are shown superimposed on 2004/05 imagery to illustrate the change in distribution of *Phragmites* and other vegetation in eleven years (Figures 3 – 6). Lines are drawn for scale to show the approximate distance from the original up-stream transect established during 2004 down to the second transect of 2015/16, illustrating the extent of invasion of *Phragmites* (primarily) out into Farmington Bay.

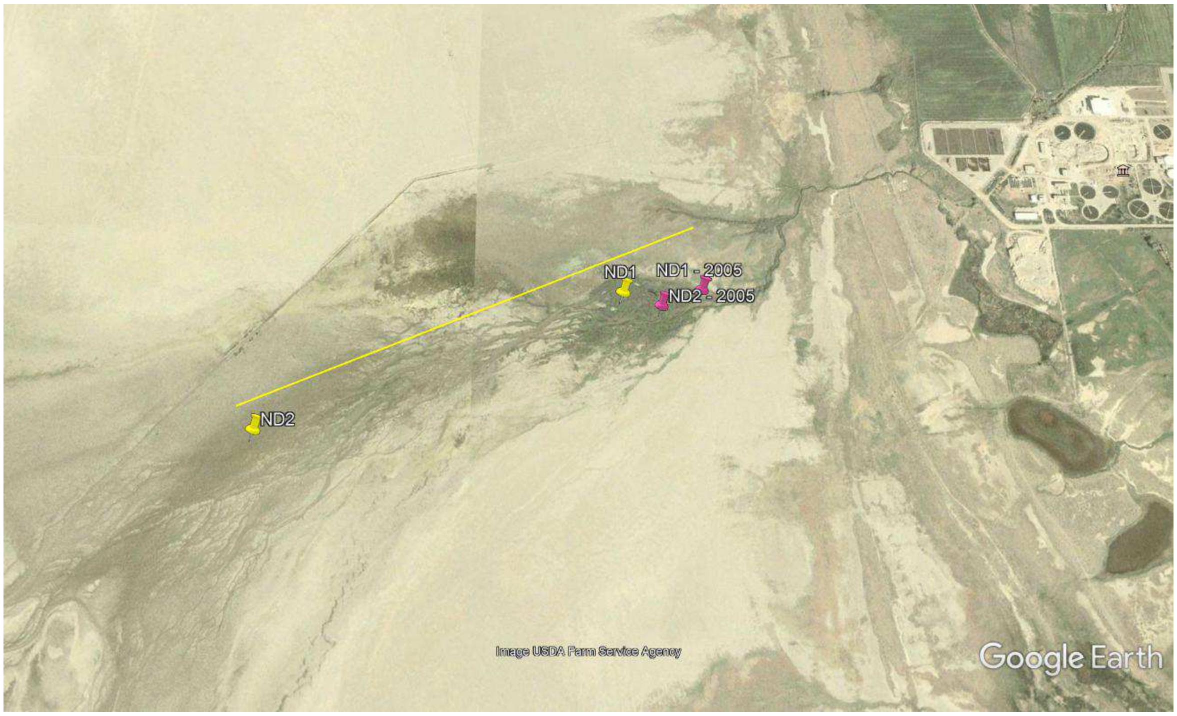

Figure 3. Image of 2004/05 and 2015/16 ND transect locations; yellow line is 1.12 km / 0.7 mi. Note the lack of emergent vegetation along more than half of the yellow line. (Google Earth, Sept 2004).

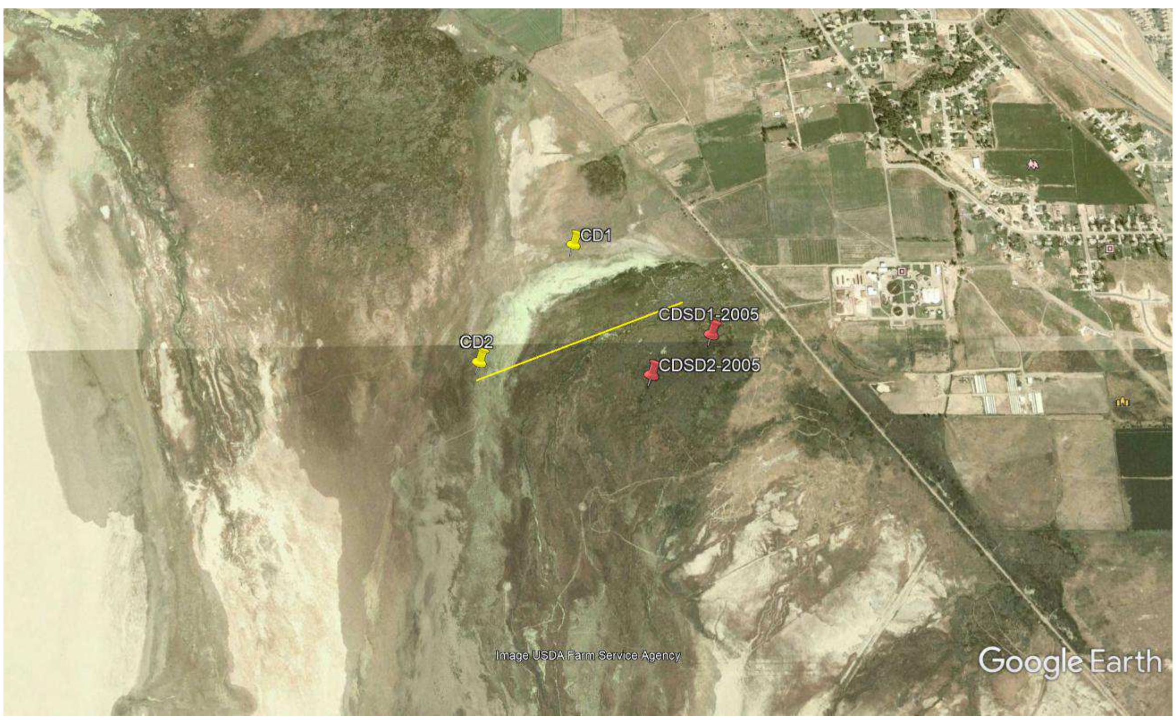

Figure 4. Image of 2004/05 and 2015/16 CD transect locations; yellow line is 804 m / 0.5 mi. (Google Earth, Sept 2004).

Figure 5. Image of 2004/05 and 2015/16 KC transect locations; yellow line is 887 m / 0.55 mi. (Google Earth, Aug 2005).

Figure 6. Image of 2004/05 and 2015/16 TU transect locations; yellow line is 560 m / 0.35 mi. (Google Earth, Aug 2005).

METRICS

Within each plot, percent cover of all living plant species and standing dead vegetation were determined and recorded. The following metrics were also recorded or collected and those that reflected significant response are reported in the results:

- Average height of the three tallest *Phragmites* stems, measured from surface of sediment to tip of uppermost leaf when held upright.
- Standing water depth from where the meter tape cannot penetrate litter or surface of humus soil layer. Average of three maximum *Phragmites* stem diameters (stem height must be at least 130 cm, except in grazed plots where tallest of remaining stems were measured).
- Average (of 3) *Phragmites* stem diameters (stem height must be at least 130 cm, except in grazed plots where tallest of remaining stems were measured).
- Stem density count of live *Phragmites* in a 25 cm 2 sub-plot randomly located within each plot.
- # Invasive species within plot.
- # Non-native species within plot.
- Taxa richness
- Litter depth measured from solid ground or impenetrable litter to highest portion of the litter.
- Litter score:
  - 0 = full sunlight through the canopy; no shading by litter.
  - 1 = minimal shading by litter; litter is not thick and sunlight penetrates to most of the ground.
  - 2 = plot is shaded by moderate litter but sunlight penetrates through at least 50% of the litter to the ground.
  - 3 = most of the plots is shaded by a thick litter layer, but some sunlight penetrates to the ground, providing diffuse light.
  - 4 = complete shading by thick litter layer; no sunlight penetrates to the ground.
- Disturbance score:
  - 0 = No Disturbance, no invasive or non-native species
  - 1 = Minimal to some disturbance (less than 25% of transect contains invasive +/or non-native species)
  - 2 = Disturbed (at least 25% -70% of transect contains invasive +/or non-native species)
  - 3 = Very Disturbed: majority of transect (> 70%) contains invasive +/or non-native species
- Seed biomass samples (once seeds were formed) of all seeds present (as total inflorescence, i.e., seeds were not separated from each inflorescence) within the stem density sub-plots, dried by species at 34° C for a minimum of three days and weighed.

Metrics added in 2016 (applied to earlier data where applicable):

- *Water flow (cm/sec) – time that the smallest visible suspended particles traveled past a submerged metric tape; measured at least three times along each transect where water was present.*
- *Water presence – water present or not (dry)*
- *Cattle Presence – cattle on site or not*

- *Discharge influence – down-gradient or not*

WATER QUALITY PARAMETERS

Water quality parameters, collected and analyzed by DWQ, were sampled in triplicate during the monthly site visits when water was present and included: ammonia, nitrate and total phosphorus. Samples were taken back to the lab, where they were filtered and analyzed with Hach Kits.

STATISTICAL EVALUATION

Relationships between the metrics were examined and compared. Several metrics were count data truncated at zero and were not normally distributed. Several other metrics were fractional (proportional) data, limited in distribution between 0 and 1, and also not normally distributed. Therefore, several regression models where the response (dependent) variables were from non-normal distributions were generated including; linear, truncated Poisson, fractional logistic, and truncated negative binomial models. Model fitness was evaluated and best-fit models were selected using log likelihood (ll), Akaikies Information Criteria (AIC) and Bayesian Information Criteria (BIC) that had the lowest values. Incidence rate ratios (IRR) and odds-ratios were used instead of regression coefficients for the non-linear models to better help interpret results. IRRs can be interpreted similarly to odds ratios or risk ratios. Robust standard errors were used in all models. Pairwise comparisons of predicted means vs. grand means from regression models were also generated, where appropriate. All statistical analyses were performed using Stata/IC 15.1 for Mac (64-bit Intel; StataCorp 2018).

RESULTS AND DISCUSSION

The intent of following the development of *Phragmites* at all sites from June through August or September was to determine whether differences in any of the measured metrics occurred among the sites that could be attributed to environmental characteristics. June proportion *Phragmites*, standing dead vegetation, and maximum height data were significantly different from July, August, and September data, which did not differ, therefore June data was excluded from additional analyses (Table 2 – 5; Figures 7 – 9).

Table 2 Fractional logistic regression of proportion *Phragmites* all months. June = baseline.

```
Fractional logistic regression                  Number of obs     =        786
                                                Wald chi2(3)      =      20.35
                                                Prob > chi2       =     0.0001
Log pseudolikelihood = -527.31724               Pseudo R2         =     0.0119
```

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
month						
July	1.67	0.25	3.50	0.00	1.25	2.23
Aug	1.68	0.24	3.64	0.00	1.27	2.22
Sept	2.15	0.59	2.81	0.00	1.26	3.67
_cons	0.50	0.05	-7.07	0.00	0.41	0.61

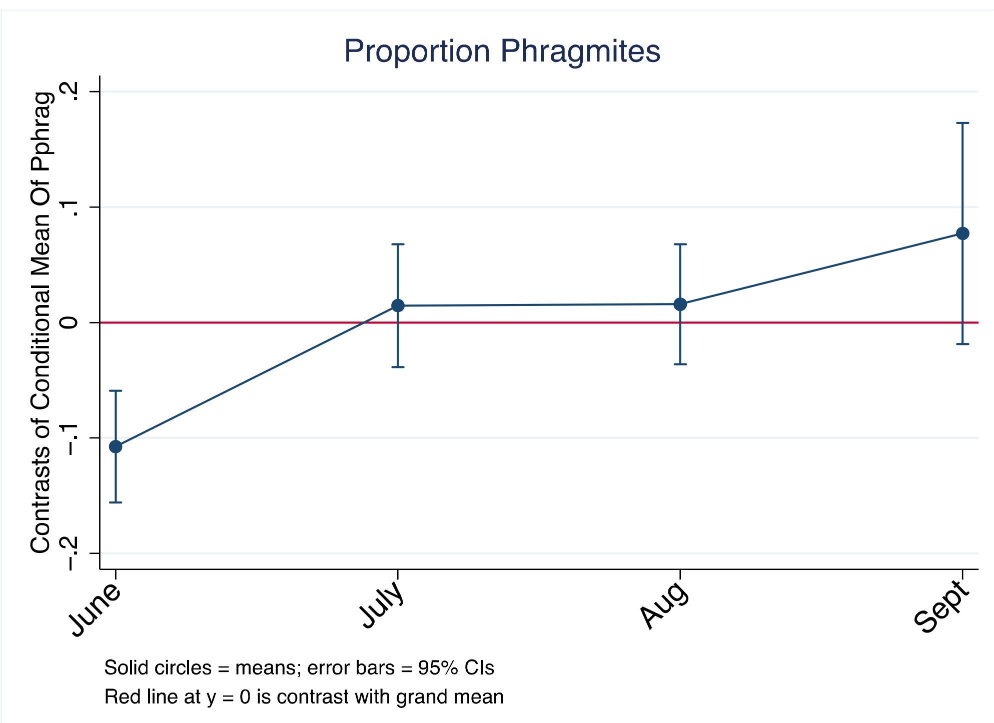

Figure 7. Contrasts of linear predictions of proportion *Phragmites* all months compared to grand mean.

Table 3 Pairwise comparisons of adjusted predictions of proportion *Phragmites* by month. VCE =robust; fractional logistic regression prediction

```
Pairwise comparisons of adjusted predictions
Model VCE     : Robust

Expression    : Conditional mean of pphrag, predict()
```

	Contrast	Delta-method Std. Err.	Unadjusted z	Unadjusted P>|z|	Unadjusted [95% Conf.	Interval]
month						
July vs June	**0.12**	**0.03**	**3.51**	**0.00**	**0.05**	**0.19**
Aug vs June	**0.12**	**0.03**	**3.66**	**0.00**	**0.06**	**0.19**
Sept vs June	**0.18**	**0.07**	**2.75**	**0.01**	**0.05**	**0.32**
Aug vs July	**0.00**	**0.04**	**0.03**	**0.97**	**-0.07**	**0.07**
Sept vs July	**0.06**	**0.07**	**0.91**	**0.36**	**-0.07**	**0.20**
Sept vs Aug	**0.06**	**0.07**	**0.90**	**0.37**	**-0.07**	**0.20**

Table 4 Fractional logistic regression of proportion DV (litter) all months. June = baseline.

```
Fractional logistic regression                   Number of obs   =        707
                                                 Wald chi2(3)    =      22.83
                                                 Prob > chi2     =     0.0000
Log pseudolikelihood = -220.03239                Pseudo R2       =     0.0187
```

pdv	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
month						
July	**0.42**	**0.08**	**-4.33**	**0.00**	**0.28**	**0.62**
Aug	**0.55**	**0.11**	**-3.00**	**0.00**	**0.37**	**0.81**
Sept	**0.46**	**0.15**	**-2.31**	**0.02**	**0.24**	**0.89**
_cons	**0.16**	**0.02**	**-15.63**	**0.00**	**0.13**	**0.20**

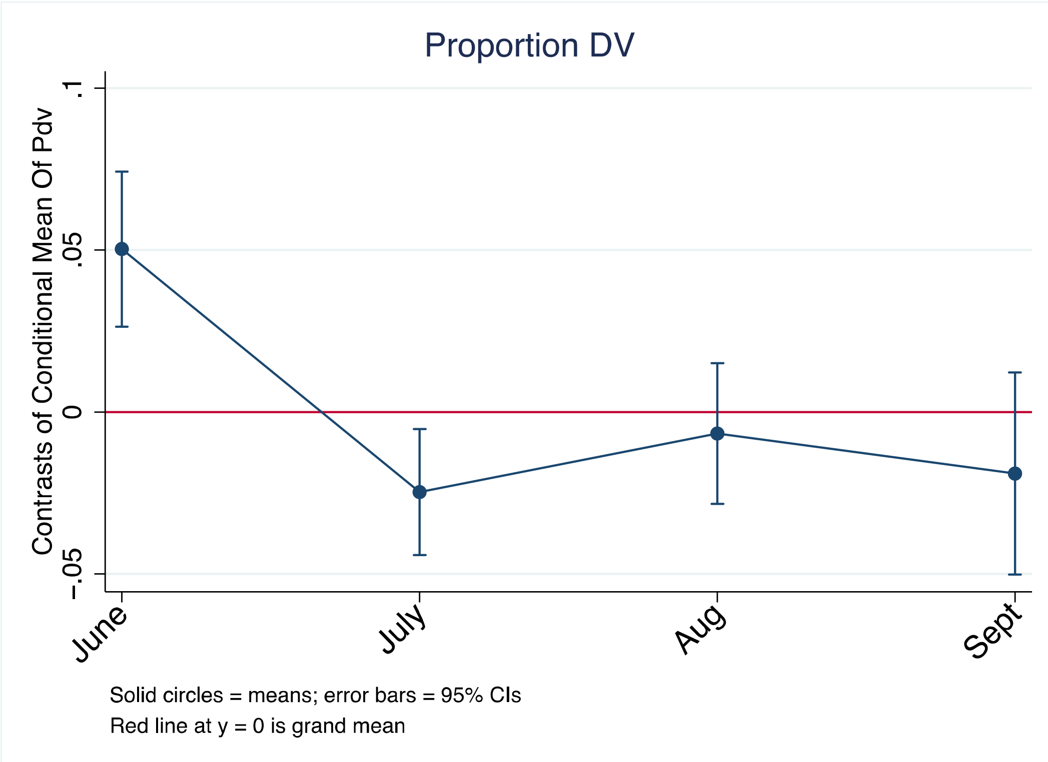

Figure 8. Contrasts of linear predictions of proportion DV all months compared to grand mean.

Table 5 Pairwise comparisons of adjusted predictions of proportion DV by month. VCE =robust; fractional logistic regression prediction

```
Pairwise comparisons of adjusted predictions
Model VCE    : Robust

Expression   : Conditional mean of pdv, predict()
```

	Contrast	Delta-method Std. Err.	Unadjusted z	P>|z|	Unadjusted [95% Conf.	Interval]
month						
July vs June	-0.08	0.02	-4.43	0.00	-0.11	-0.04
Aug vs June	-0.06	0.02	-3.10	0.00	-0.09	-0.02
Sept vs June	-0.07	0.02	-2.83	0.00	-0.12	-0.02
Aug vs July	0.02	0.02	1.18	0.24	-0.01	0.05
Sept vs July	0.01	0.02	0.26	0.80	-0.04	0.05
Sept vs Aug	-0.01	0.02	-0.53	0.60	-0.06	0.03

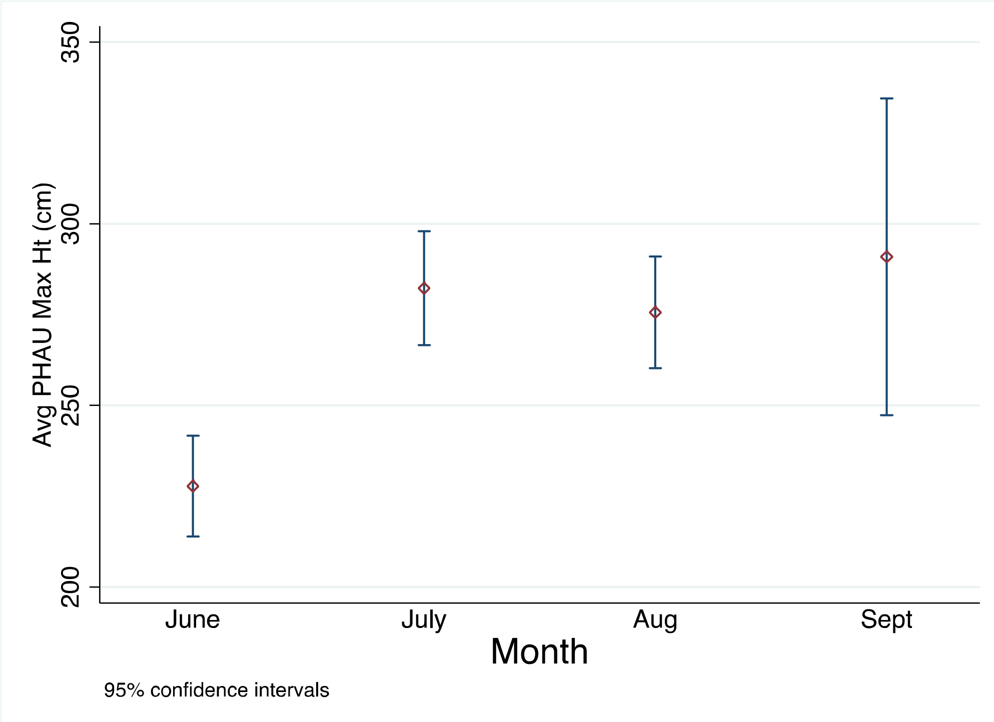

Figure 9. Average maximum height *Phragmites* all months. Means and 95% CIs.

Cattle used for the control of *Phragmites* was effective when grazing occurred. Grazed sites within our study had a significantly greatly reduced proportion of *Phragmites* (Table 6, Figure 10).

Table 6 Fractional logistic regression of grazing effects (cattle present) on proportion *Phragmites*

```
Fractional logistic regression                  Number of obs     =        506
                                                Wald chi2(1)      =      50.29
                                                Prob > chi2       =     0.0000
Log pseudolikelihood = -333.36122               Pseudo R2         =     0.0461
```

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
cattlepresent						
0	1	(base)				
1	.2668376	.0497087	-7.09	0.000	.1852159	.3844286
_cons	1.122314	.0912861	1.42	0.156	.9569291	1.316282

Note: _cons estimates baseline odds.

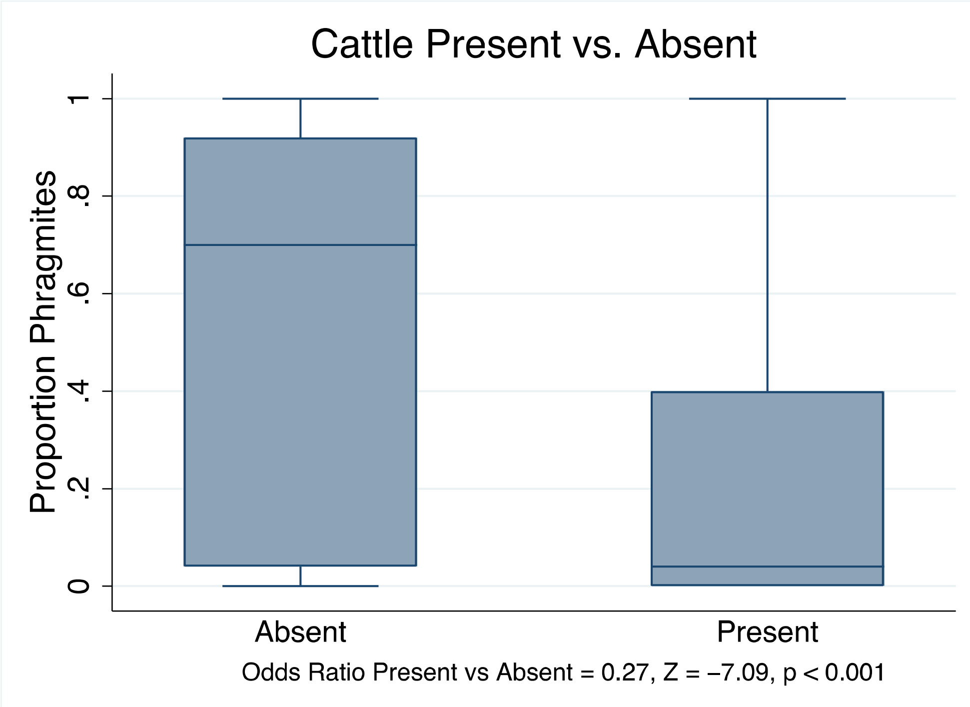

Figure 10. Proportion *Phragmites* with cattle absent versus cattle present.

Since cattle grazing was effective in reducing the proportion of *Phragmites*, we were curious whether plant taxa richness would increase in areas grazed by cattle. This was not the case in that there was no difference in taxa richness in areas with and without cattle (Table 6). Plausible explanations for the lack of increase in richness could be attributed to cattle reducing richness in addition to proportion *Phragmites* (they reduced the presence of all or most species including *Phragmites*), there may be allelopathic implications of *Phragmites* on the establishment of other species (Uddin 2014), and most likely, sites may not have received grazing treatment long enough for changes in the plant community

```
Poisson regression                              Number of obs     =        506
                                                LR chi2(1)        =       0.73
                                                Prob > chi2       =     0.3942
Log likelihood = -670.26384                     Pseudo R2         =     0.0005
```

taxarichness	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
1.cattlepresent	.0746781	.087052	0.86	0.391	-.0959408	.2452969
_cons	.3756376	.0415945	9.03	0.000	.2941138	.4571613

INFLUENCE OF SALINITY, SEDIMENT TOXICITY AND SURFACE WATER NUTRIENTS ON *PHRAGMITES* PROPORTION AND HEIGHT

Having identified management of *Phragmites* with grazing as an effective influence on its distribution, the question remained as to whether nutrients or other environmental factors influenced its distribution around Farmington Bay. Because cattle effected most other response variables, data where cattle were present were removed from the following analyses (June data were also removed) to determine the extent of other environmental effects on *Phragmites* proliferation.

The proportion of *Phragmites* varied among sites with that down-gradient from the Central Davis Sewer District discharge (CD 1 & 2), Lake Front Duck Club (LF 1 & 2), and north of Turpin Unit (TU2) being the highest (Figure 11); these sites had moderate to low water levels (data not presented). Most of the sites with the lowest proportion *Phragmites* had the greatest volume of water Kays Creek (KC 1), Northwest Oil Drain (OD1), and North Davis Sewer District discharge (ND1); or were more saline and dry (OD2 and TU1).

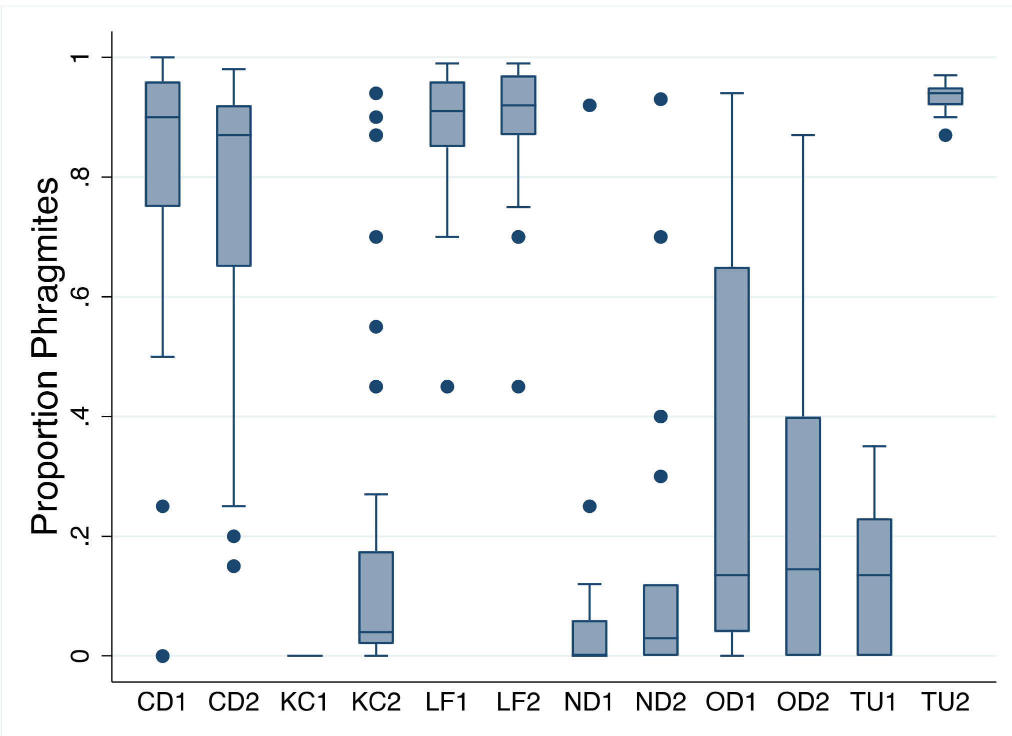

Figure 11. Proportion *Phragmites* all sites excluding June data and where cattle were present, 2005, 2011, 2015, and 2016.

A higher proportion of *Phragmites* was evident at sites with both moderate salinity (12 times higher) and moderate sediment toxicity (twice as high) indicating a certain level of tolerance to both sediment conditions (Table 8). There were significant interactions between the effect of salinity and sediment toxicity on proportion *Phragmites* as well, which would require further study to understand.

Table 8 Fractional logistic regression of proportion *Phragmites* and salinity and sediment toxicity

Fractional logistic regression	Number of obs	=	401
	Wald chi2(8)	=	335.29
	Prob > chi2	=	0.0000
Log pseudolikelihood = -251.87125	Pseudo R2	=	0.0924

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
salinity						
1	12.27	3.03	10.16	0.00	7.57	19.90
2	1.44	0.38	1.38	0.17	0.86	2.40
sedimenttoxicity						
1	2.10	0.68	2.31	0.02	1.12	3.95
2	0.31	0.11	-3.17	0.00	0.15	0.64
salinity#sedimenttoxicity						
1 1	0.01	0.01	-8.26	0.00	0.00	0.04
1 2	0.11	0.06	-4.06	0.00	0.04	0.32
2 1	0.45	0.18	-2.03	0.04	0.20	0.97
2 2	0.48	0.24	-1.49	0.14	0.19	1.26
_cons	1.10	0.22	0.46	0.64	0.74	1.64

When proportional *Phragmites* was compared with surface water nutrients alone (as ammonia, nitrate, and phosphate), there was a significant positive influence of phosphate on *Phragmites* and slightly negative influence of ammonia and nitrate (Table 9, Figure 12).

Table 9 Fractional logistic regression of proportion *Phragmites* versus surface water nutrients

Fractional logistic regression	Number of obs	=	260
	Wald chi2(3)	=	29.95
	Prob > chi2	=	0.0000
Log pseudolikelihood = -135.27596	Pseudo R2	=	0.2444

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
ammonia	0.71	0.05	-4.65	0.00	0.61	0.82
nitrate	0.00	0.00	-2.53	0.01	0.00	0.09
phosphate2	1.73	0.21	4.44	0.00	1.36	2.20
_cons	3.84	0.97	5.33	0.00	2.34	6.29

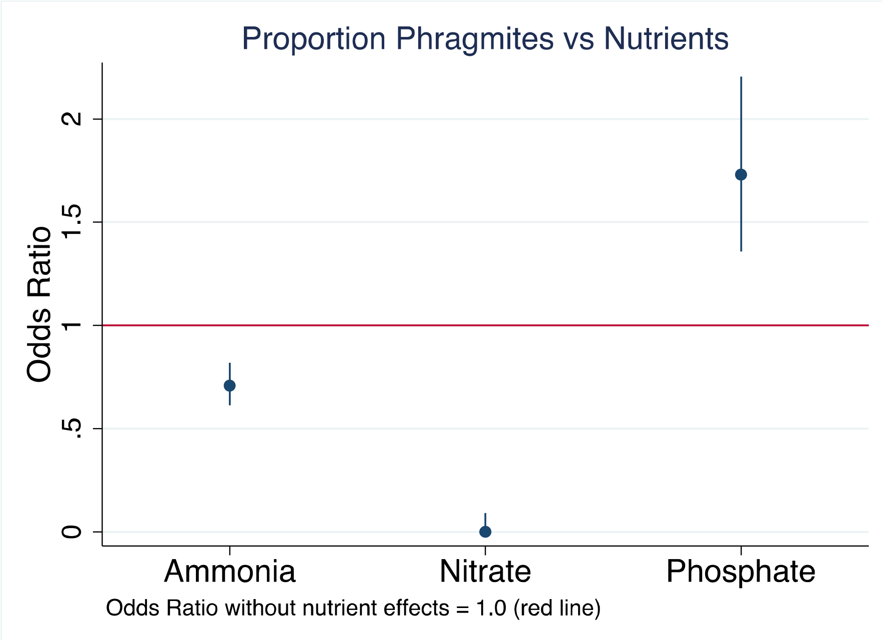

Figure 12. Proportion *Phragmites* versus surface water nutrients, ammonia, nitrate, and phosphate. Mean and 95% CIs.

When proportion *Phragmites* was compared to salinity, sediment toxicity and surface water nutrients, surface water phosphate had the strongest effect (Table 10). That *Phragmites* is tolerant of salinity to a certain extent is further supported by Carling et al. (2013) who showed an inverse relationship between invasive macrophytes of Farmington Bay and pore water salinity but not with higher concentrations of trace elements (eg., metals) with increasing distance out into the bay.

```
Fractional logistic regression                  Number of obs     =        260
                                                Wald chi2(10)     =     306.64
                                                Prob > chi2       =     0.0000
Log pseudolikelihood = -122.40831               Pseudo R2         =     0.3162
```

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
salinity						
0	1	(base)				
1	4.947479	1.996442	3.96	0.000	2.24337	10.91106
2	.3609922	.1252604	-2.94	0.003	.182869	.7126161
sedimenttoxicity						
0	1	(base)				
1	.0133465	.0113932	-5.06	0.000	.0025046	.0711207
2	.2729606	.1102298	-3.22	0.001	.1236969	.602339
ammonia	.389095	.0748652	-4.91	0.000	.2668561	.567328
nitrate	.0001111	.0001158	-8.73	0.000	.0000144	.0008573
phosphate2	15.09072	6.984955	5.86	0.000	6.091432	37.38529
salinity# sedimenttoxicity						
0 0	1	(base)				
0 1	1	(base)				
0 2	1	(base)				
1 0	1	(base)				
1 1	1	(empty)				
1 2	.2573732	.429488	-0.81	0.416	.0097754	6.776322
2 0	1	(base)				
2 1	1.542219	.8614091	0.78	0.438	.5160669	4.608782
2 2	.9110156	.6072791	-0.14	0.889	.2466712	3.364598
_cons	10.28348	3.758286	6.38	0.000	5.024042	21.0488

Average maximum heights of *Phragmites* at sites where *Phragmites* occurred along a 100 m transect were compared from 2011, 2015, and 2016, June months and cattle present data excluded (Figure 13). *Phragmites* at Central Davis Sewer District discharge (CD) and Lakefront Duck Club (LF, control) regularly approached 4m in height, well above *Phragmites* heights at all remaining sites. The two most saline sites, Oil Drain 2 (OD2) and Turpin Unit 1 (TU1) had the shortest plants, which were consistently under 2 m.

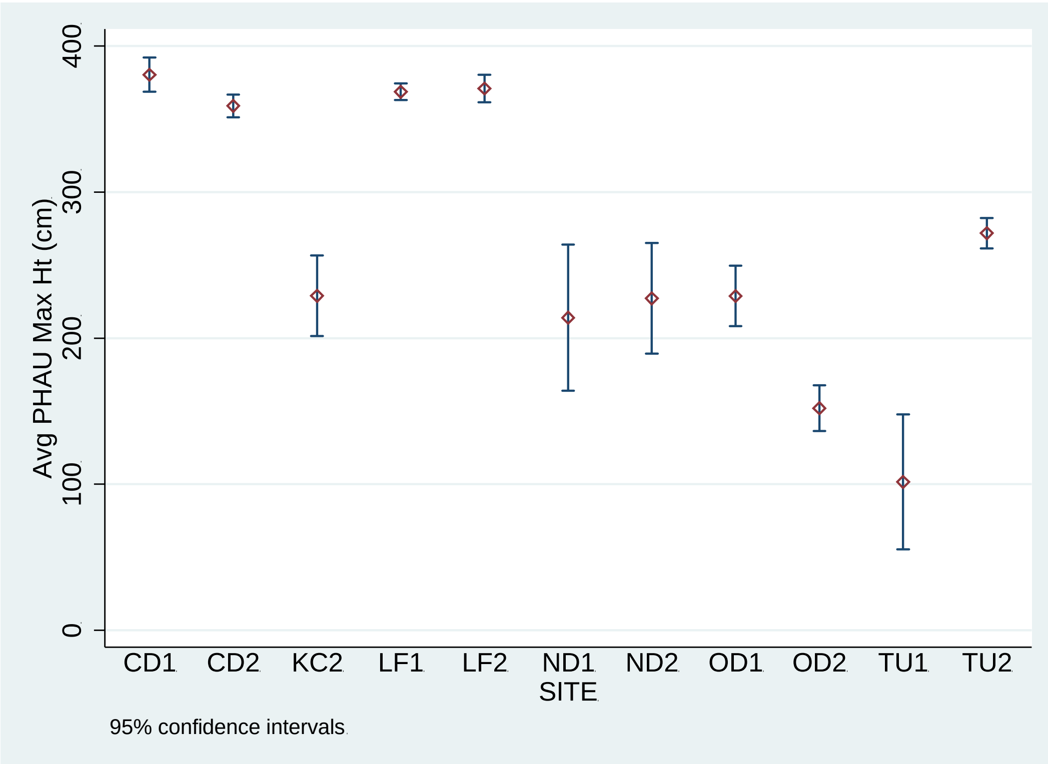

Figure 13. Comparison of average maximum height of *Phragmites* at sites where *Phragmites* occurred along a 100 m transect, 2011, 2015, 2016, June months and cattle present months excluded. CD1 and 2: Central Davis Sewer District discharge, KC: Kays Creek: LF1 and 2: Lakefront Duck Club; ND1 and 2: North Davis Sewer District discharge; OD1 and 2: Oil Drain; TU1 and 2: Turpin Unit outflow.

A linear regression of average maximum height *Phragmites* versus salinity, sediment toxicity, surface water nutrients, and disturbance score indicates that sites associated with the highest levels of phosphate had the tallest *Phragmites* and had the highest disturbance score (highest proportion of *Phragmites* or other non-native invasive plants along the transect; Table 11).

Table 11 Linear regression of average maximum height of *Phragmites* versus salinity, sediment toxicity, surface water nutrients, and disturbance score

Linear regression

Number of obs	=	207
F(13, 193)	=	66.66
Prob > F	=	0.0000
R-squared	=	0.8154
Root MSE	=	37.817

avgphaumaxhtcm	Coef.	Robust Std. Err.	t	P>|t|	[95% Conf.	Interval]
salinity						
0	0	(base)				
1	-90.11121	9.133684	-9.87	0.000	-108.1259	-72.09655
2	-130.8288	26.48869	-4.94	0.000	-183.0733	-78.58436
sedimenttoxicity						
0	0	(base)				
1	-61.90315	19.00291	-3.26	0.001	-99.38319	-24.4231
2	-47.8311	12.01458	-3.98	0.000	-71.52783	-24.13436
salinity# sedimenttoxicity						
0 0	0	(base)				
0 1	0	(base)				
0 2	0	(base)				
1 0	0	(base)				
1 1	0	(empty)				
1 2	124.4008	35.85019	3.47	0.001	53.69232	195.1092
2 0	0	(base)				
2 1	18.43413	10.86435	1.70	0.091	-2.993972	39.86223
2 2	-93.45906	25.97073	-3.60	0.000	-144.6819	-42.23617
ammonia	-12.84022	3.17952	-4.04	0.000	-19.11128	-6.56915
nitrate	-56.35343	26.66351	-2.11	0.036	-108.9427	-3.764144
phosphate2	34.77788	8.792368	3.96	0.000	17.43642	52.11935
disturbancescore						
1	0	(base)				
2	79.30316	13.2459	5.99	0.000	53.17786	105.4285
3	147.5819	14.26152	10.35	0.000	119.4535	175.7104
year						
2015	0	(base)				
2016	-115.9551	26.64055	-4.35	0.000	-168.4991	-63.4111
_cons	349.3769	36.69512	9.52	0.000	277.002	421.7519

INFLUENCE OF WATER PRESENCE AND FLOW ON PROPORTION AND HEIGHT OF *PHRAGMITES*

Along with the primary question of whether elevated levels of nutrients influence the spread, distribution and robustness of *Phragmites* populations around Farmington Bay is the consideration of whether other factors also play a role in its proliferation. While key environmental factors, such as sediment toxicity and salinity significantly affect the distribution and stature or robustness of *Phragmites* populations, we were particularly interested to see whether hydrology was also important since the hydrology of Farmington Bay is highly manipulated as a result of human water use.

A Kruskal-Wallis chi square test between proportion *Phragmites* and water present or absent showed no significant effect of the presence of water (x2 = 44.34, d.f. = 40, p = 0.29; Figure 14) although the median proportion was twice as great where water was present compared to dry sites. A possible explanation includes tolerance of *Phragmites* to lack of inundation later in the growing season after spring precipitation and runoff have subsided and / or evaporated. It could also suggest that the water table was within reach of the *Phragmites* roots in most cases. However, *Phragmites* at sites that were more saline (and became dry as surface water evaporated) had the shortest (stunted) plants, indicating *Phragmites* has limited drought and salt tolerance. *Phragmites* height was significantly influenced by presence of water, further supporting a limited tolerance to drought (Figures 15).

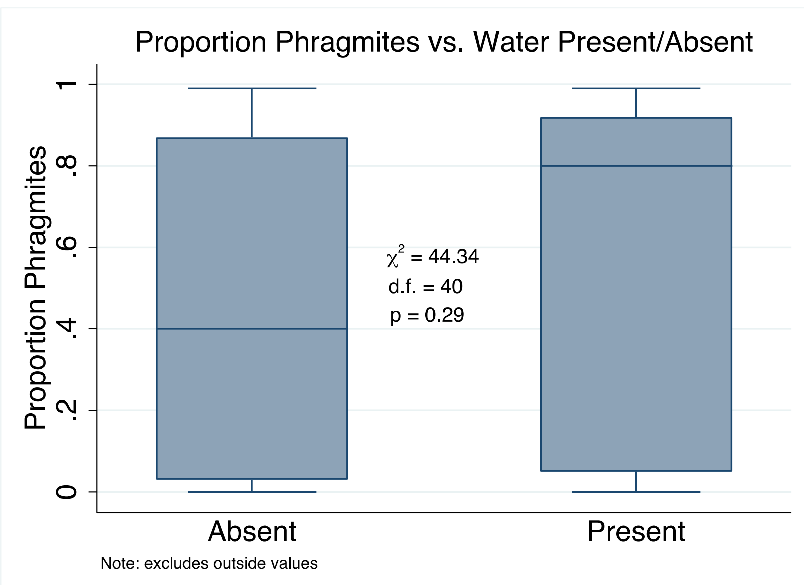

Figure 14. Proportion *Phragmites* versus surface water presence and absence (data from June and where cattle were present removed).

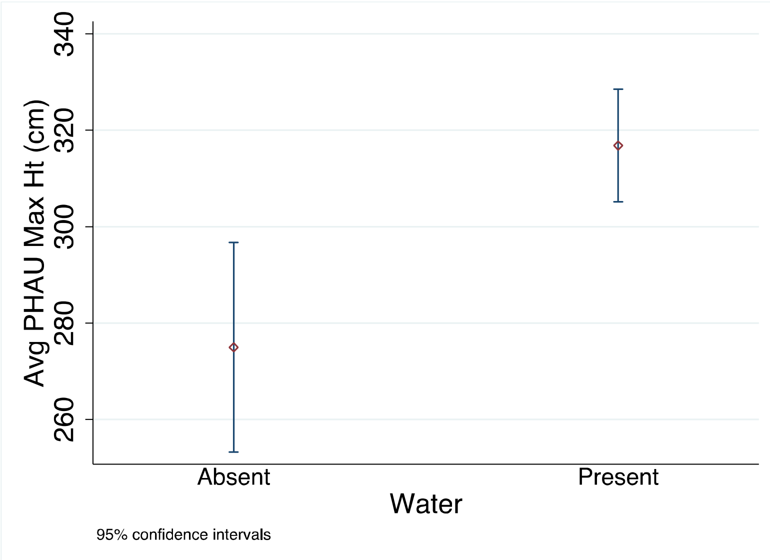

Figure 15. *Phragmites* average maximum height versus water presence and absence (data from June and where cattle present were removed).

Proportion *Phragmites* was also compared with water depth and flow rate (Tables 12 and 13). Depth of water significantly negatively affected proportion of *Phragmites,* whereas flow rates did not.

Table 12 Fractional logistic regression proportion *Phragmites* versus water depth and flow rate

Fractional logistic regression	Number of obs	=	75
	Wald chi2(2)	=	6.12
	Prob > chi2	=	0.0469
Log pseudolikelihood = -49.902762	Pseudo R2	=	0.0401

pphrag	Odds Ratio	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
flowcmsec	1.43	0.44	1.15	0.25	0.78	2.62
h2odepthcm	0.90	0.05	-2.10	0.04	0.81	0.99
_cons	1.08	0.28	0.29	0.77	0.65	1.78

Highest proportions *Phragmites* were located in areas where water depths ranged from zero to 20 cm (Figure 16). Of note, *Phragmites* at K1 and the OD1, ND1 and ND2 discharge sites had one of the lowest proportion of *Phragmites* compared to the rest of the sites and they frequently had water depths well over 20 cm (OD1 having somewhat variable water depths and proportion; see Figure 11).

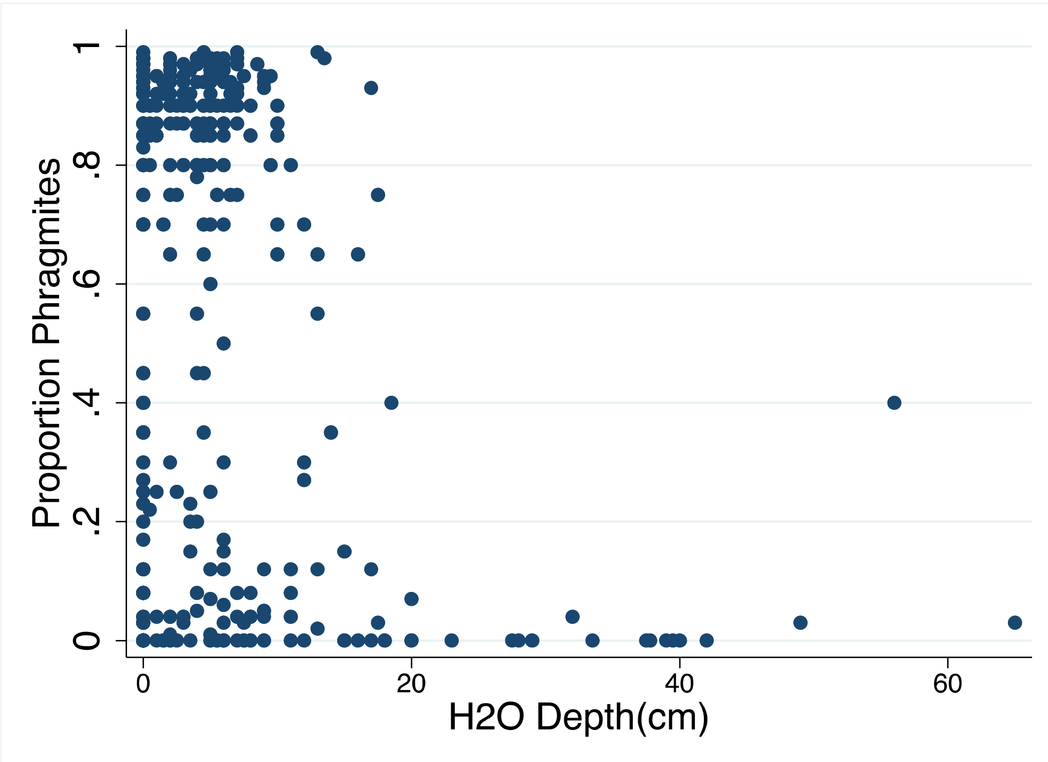

Figure 16. Proportion *Phragmites* versus water depth (cm), 2015 and 2016, (June data and where cattle were present excluded).

Alternatively, water flow was a significant predictor of *Phragmites* height (Table 13). Note that water flow rate maximum was never higher than 5 cm / sec, with an average of 1.3 cm / sec (data not presented). Water depth also negatively affected *Phragmites* height but not quite significantly at the $p \leq 0.05$ level (Table 12). Comparisons between models of *Phragmites* height vs water flow and depth when modeled separately and combined showed that both flow and depth were important factors when considered together (lowest LL, AIC, and BIC) although they were not particularly good for explaining *Phragmites* height ($R2 = 0.10$, $p = 0.06$) and other factors not modeled affected height (Tables 13 and 14).

Table 13 Linear regression of average maximum height *Phragmites* (cm) versus water depth (cm) and flow rate (cm / sec)

```
Linear regression                                   Number of obs    =        56
                                                    F(2, 53)         =      2.93
                                                    Prob > F         =    0.0621
                                                    R-squared        =    0.0977
                                                    Root MSE         =    95.767
```

avgphaumax~m	Coef.	Robust Std. Err.	t	P>|t|	[95% Conf.	Interval]
h2odepthcm	**-3.83**	**2.06**	**-1.86**	**0.07**	**-7.97**	**0.30**
flowcmsec	**39.65**	**16.40**	**2.42**	**0.02**	**6.76**	**72.54**
_cons	**287.00**	**19.02**	**15.09**	**0.00**	**248.85**	**325.14**

Table 14 Goodness- of- fit comparisons of linear regression of average maximum height *Phragmites* (cm) versus water depth (cm) and flow rate (cm / sec)

	N	ll (null)	ll (model)	df	AIC	BIC
Depth and flow	56	-336.26	-333.39	3	672.77	678.85
Depth	301	-1792.01	-1790.16	2	3584.29	3591.70
Flow	57	-342.02	-339.71	2	683.42	687.51

Seed biomass (TSA g/m^2) varied among sites and could be explained from environmental factors (Figure 17, Table 15). Consistent with other metrics, median seed biomass was similar at CD 1 & 2, LF 1 & 2, and TU2. Salinity (and dryness) likely affected seed biomass at sites OD2 and TU1, which were both at the edge of a playa and were dry most dates sampled. KC1, OD1, ND1 and ND2 had similar hydrology, being fairly fresh deep water sites compared to the other sites and had limited presence of *Phragmites*, rendering low seed biomass. KC2 was located in a site that was dense with *Phragmites* litter from previous years, which likely resulted in a late development and growth due to shading. While plants at K2 extended in height comparable to other sites once they broke through the litter (see Figure 13), their seed production also lagged. Seed biomass was significantly correlated with other variables, moderate sediment toxicity, highest proportion and tallest *Phragmites*, and was inversely correlated with water depth, which are presented in Table 16 and Figure 18.

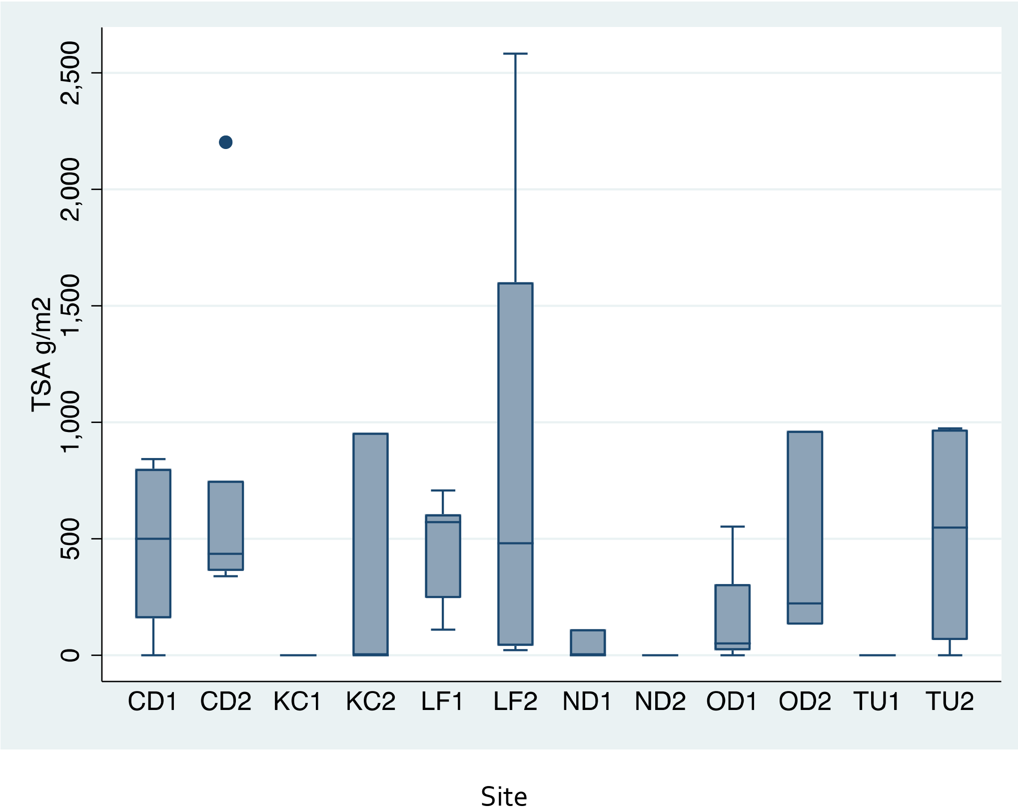

Figure 17. Seed biomass (TSA g/m^2) of *Phragmites* during 2015 and 2016.

Table 15 Generalized negative binomial regression of see biomass (TSA g/m²) across sites

```
Generalized negative binomial regression          Number of obs     =         50
                                                  Wald chi2(8)      =          .
                                                  Prob > chi2       =          .
Log pseudolikelihood = -277.48635                 Pseudo R2         =     0.0712
```

tsagm2	IRR	Robust Std. Err.	z	P>|z|	[95% Conf.	Interval]
Site						
CD1	12.47666	10.9009	2.89	0.004	2.25113	69.1506
CD2	21.85717	19.95254	3.38	0.001	3.652293	130.8043
KC1	6.95e-23	.	.	.	.	.
KC2	8.519796	9.93769	1.84	0.066	.8660995	83.809
LF1	12.53236	10.60443	2.99	0.003	2.386588	65.80949
LF2	24.08724	21.98066	3.49	0.000	4.027433	144.0608
ND2	6.95e-23	.	.	.	.	.
OD1	4.363732	4.713542	1.36	0.173	.5253173	36.24887
OD2	11.74803	11.29557	2.56	0.010	1.784624	77.33632
TU1	6.95e-23	.	.	.	.	.
TU2	13.83186	12.95007	2.81	0.005	2.207716	86.65979
_cons	37.3992	30.8464	4.39	0.000	7.426799	188.3315

Table 16 Generalized negative binomial regression of seed biomass (tsagm2) versus other variables

	IRR	Std. Err.	z	P>z	[95% Conf.	Interval]
salinity						
1	0.14	0.12	-2.37	0.02	0.03	0.71
2	0.85	0.41	-0.34	0.73	0.33	2.18
Sediment toxicity						
1	1.02	0.50	0.03	0.97	0.39	2.68
2	0.08	0.09	-2.13	0.03	0.01	0.81
pphrag	69.41	162.59	1.81	0.07	0.70	6843.90

avgphaumaxhtcm	0.98	0.01	-1.74	0.08	0.97	1.00
h2odepthcm	0.84	0.05	-3.29	0.00	0.75	0.93
phaustemdensitym2	1.00	0.01	0.11	0.91	0.98	1.02
Constant	11817.13	25560.44	4.34	0.00	170.36	819709.90

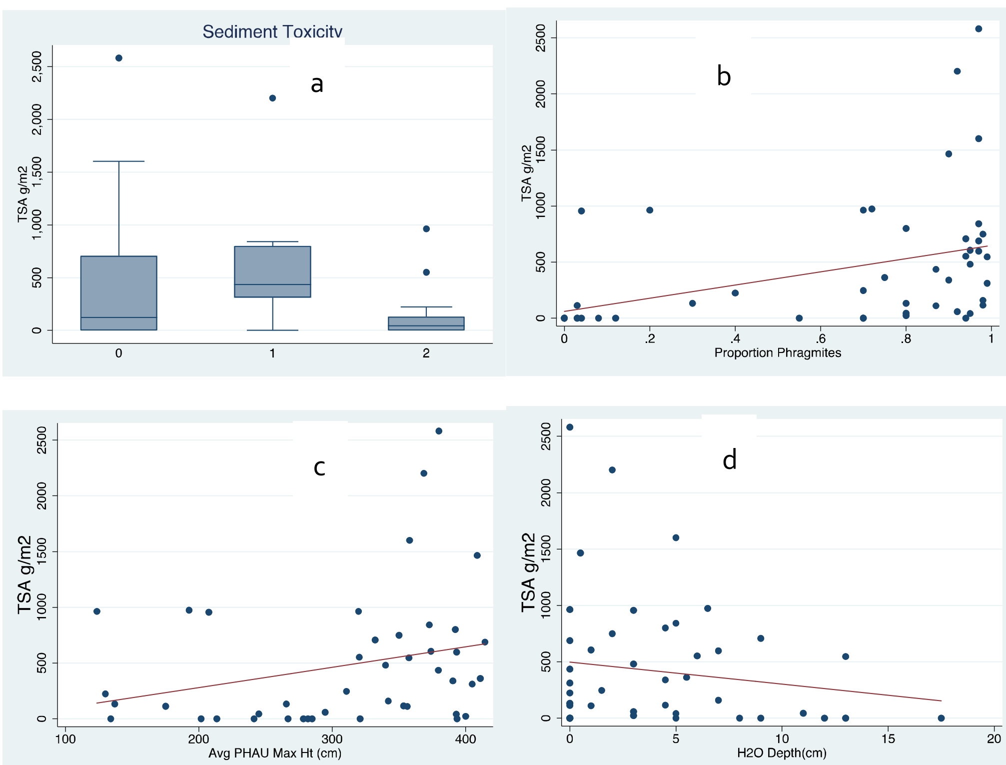

Figure 18. Seed biomass versus a) sediment toxicity, b) proportion *Phragmites*, c) average maximum height (cm), and water depth (cm); all sites, 2015 and 2016.

SUMMARY

Many factors likely influence the extent and robustness of *Phragmites* around Farmington Bay. We found surface water nutrient and water quantity to be the most important factors influencing *Phragmites* condition around Farmington Bay, similar to that remotely sensed and modeled by Long at al. (2017), however we identified additional variables related to management of water and *Phragmites*, salinity relative to hydrology and post-Great Salt Lake flood dynamics, and sediment toxicity that give *Phragmites* a competitive edge over other wetland plants and invasion out onto mudflats. Below, a conceptual path model illustrates the multiple drivers of *Phragmites* condition as measured by proportion, height, stem density and seed biomass (Figure 19). In the diagram, oval shapes are known as latent variables, which are emergent properties derived from measured variables. In our case, *Phragmites* condition can be considered a latent variable estimated by the measured variables: height, proportion, stem density, and seed biomass. Small circles with an epsilon represent the amount of variability for each factor not explained in our model (error).

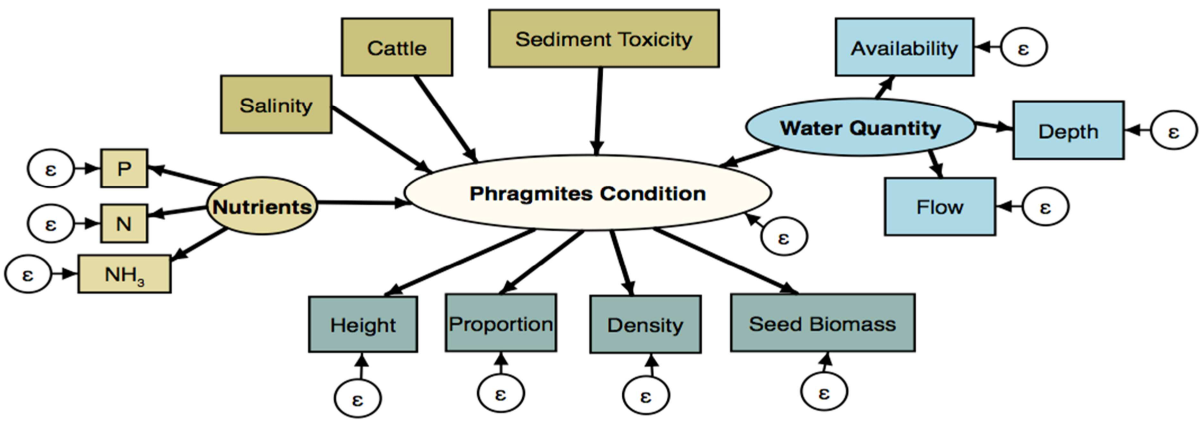

Figure 19. Conceptual structural equation model of driving factors of *Phragmites* invasion of Farmington Bay wetlands.

We found that elevated phosphates associated with surface water, moderate salinity and moderate sediment toxicity are important factors that correlated with the highest proportion (determined as percent cover) and greatest canopy height (as average maximum height). Other factors that contribute to *Phragmites* proportion and robust stature were water depth between zero and 20 cm, and flow rates up to 5 cm / sec, respectively. Cattle were effective when actively grazing, but without additional control mechanisms, sites filled in vigorously when cattle were not returned to the site the following year. These factors have important management implications for areas that use water and cattle (or mechanical mowing) as control agents of *Phragmites*.

Also of important note, highest seed biomass was associated with areas of moderate sediment toxicity, highest proportion and tallest *Phragmites*, and areas that had less than 20 cm of or no water, which establishes perpetual supplementation to the seed banks of the largest stands we sampled and may contribute to proliferation within these highly infested areas. *Phragmites* has been shown to respond to elevated sediment nutrients by producing greater floret and inflorescence production and larger stands of *Phragmites* produce significantly more viable seeds (Kettenring et al. 2011). Further, when stands of

Phragmites extend in distances greater than 500 m, genetic diversity and viability of the seeds increases greatly (Kettenring et al. 2011; McCormick 2016). Although we did not test seed viability, seed production of *Phragmites* at CD, LF, and TU2 would likely meet these criteria sufficiently well. Of these sites, one was down-gradient of a discharge (CD), one was our control site (LF) and the other was grazed for several years but not during most of the 2016 season when robust *Phragmites* growth returned (TU2), illustrating the complexity of factors that drive *Phragmites* invasion.

Higher concentrations of surface water phosphorus was reported at near shore sites of eastern Farmington Bay by Schulle (2008). While elevated surface water phosphorus and other factors reported here contribute to the establishment and spread of invasive *Phragmites*, legacy deposition of sediment-bound phosphorus, was demonstrated to be high and fairly uniform in concentration during the last 150 years or so, despite increased loading in recent history (Meyers et al. 2006) and could play an important role in sustaining healthy stands of *Phragmites* around Farmington Bay. Meyers et al. (2006) found an exception along the eastern shore of Farmington Bay where sediment phosphorus concentrations were even higher at sites were macrophytes occur, and postulated that the increased levels were due to biogeochemical sediment – pore water interactions within the root zones of the plants where sediment can act as a phosphorus source during oxidizing sediment conditions of the growing season and a phosphorus sink when P-rich plant material decomposes in reducing conditions (Hupfer and Dollan 2003).

Tolerance to moderate levels of salinity and sediment toxicity undoubtedly gives *Phragmites* the competitive advantage over other wetland macrophytes in addition to its ability to increase bioavailability of sediment phosphorus to support its aggressive establishment on mudflats of Farmington Bay. These *Phragmites*-invaded mudflats were higher in salinity after Great Salt Lake flooded during the 1980s than they are today and because of the salt, they were open and sparsely vegetated with pickleweed during dry years and lush with cosmopolitan (alkali) bulrush (*Bolboschoenus maritimus*) during wet years (Miller and Hoven 2007; Hoven 2011). Prior to the *Phragmites* invasion we have documented from 2004 through 2016, these mudflats were heavily used by shorebirds (Manning and Paul 2002; Cavitt 2007). Recently, an estimated 93 km^2 of Great Salt Lake wetlands have been invaded by *Phragmites* as of 2015 (Long et al. 2017), much of which include the fringing mudflats of Farmington Bay, particularly areas where water has leached salts from the sediment. This widespread invasion is so pervasive around Farmington Bay's shore that our control site was not significantly different in percent cover, canopy height or our other metrics than sites down gradient of a sewer treatment facility discharge. While *Phragmites* likely established more readily at point sources as a result of elevated surface water phosphorus and / or persistent shallow water during early months of establishment though mid-summer or longer, it is no longer constrained to nor more robust at our discharge sites than other fresh to brackish locations around Farmington Bay.

Far more relevant is the loss of saline moist and shallowly flooded wetlands that used to characterize Farmington Bay. These wetlands are highly important for producing macroinvertebrates that shorebirds and other waterbirds depend upon for forage and for providing nesting and loafing habitat where approaching predators can be seen due to an open, unvegetated setting. Farmington Bay (along with the other 4 bays of Great Salt Lake) is a globally important bird area as recognized by Birdlife International and the National Audubon Society because of the many birds that depend on its exceptional habitat, including its food base and, in the case of Farmington Bay, its shallow water (Evans and Martinson 2008).

Future research and management of these diminishing wetlands should prioritize what can be done to minimize further loss of habitat related to continued expansion and invasion by *Phragmites* because it isn't clear that reduced surface water phosphorus loading would make a difference when sediment phosphorus levels in Farmington Bay are naturally elevated and have been relatively unchanged through our recent human history (Meyers et al. 2006). It may be that complete eradication of the already invaded areas that fringe the upper shoreline of the lake and below the meander line is too cost prohibitive to accomplish due to the amount of chemicals, labor and equipment necessary to address the problem. Additionally, a continuous supply of seeds from un-controlled invasive populations that are situated higher in the watershed will ultimately make down-gradient control measures counterproductive unless upstream populations are controlled. It may also be that most of the invaded mudflats of Farmington Bay are irreversibly altered by a dense network of roots and rhizomes and litter build-up from *Phragmites* unless they are flooded with Great Salt Lake hypersaline water, which would effectively return the wetlands to their former unvegetated state.

To date, tremendous efforts and resources have been dedicated to research and control of *Phragmites* in wetlands of Great Salt Lake, with some areas showing significant control. While it is important to continue efforts to control it, our research shows a dire need to treat the advancing or leading edge of *Phragmites* so that the saline moist and shallowly flooded habitat that remains is conserved and protected for shorebirds and their aquatic food chain. Long et al. (2017) estimated that 9.6 km2 of open fresh water influenced shoreline (both above and below the meander line) of Farmington Bay and south of Willard Bay remains suitable for *Phragmites* invasion. Valuable information on best management practices for controlling invasive *Phragmites* with emphasis on the need to understand how to replace invaded areas with native wetland plants has been identified (Hazelton et al. 2014; Rohal et al. 2017 and 2018). While this is profoundly important and necessary for restoring wildlife habitat value to invaded emergent marsh and wet meadow wetlands, it is equally important to note that the *Phragmites*-invaded saline mudflats are increasingly at risk of being severely diminished as a wetland habitat type of Great Salt Lake. These mudflats (including those within saline playas) need to be protected from further *Phragmites* invasion and preserved in their unvegetated state, which provides the highest habitat value for shorebirds than any other wetland type of Great Salt Lake.

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