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Ecological Characteristics of Great Salt Lake Fringe Wetlands

Purpose: FY2012-WPDG :: Develop monitoring and assessment (M&A) framework for GSL fringe wetlands (FRNG)

Contract: CD968137-01

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1.0 Introduction

Extensive bands of lacustrine marsh lie along the eastern shoreline of Great Salt Lake (GSL). These highly productive wetlands occupy a hydrologic gradient between GSL and adjacent uplands and a salinity gradient between freshwater and hypersaline ecosystems. In spite of this, or perhaps because of it, these ecosystems support substantial populations of both resident and migratory waterfowl and shorebirds. These wetlands also serve as a final physical and biogeochemical filter for sediments, nutrients, and trace metals released from point and non-point sources flowing from the rapidly growing Wasatch Front, before discharging to mudflats and open water portions of the lake. There is a clear need to develop monitoring tools and an assessment framework that will ensure that the ecological functions and designated uses of these systems are maintained for future generations.

Healthy fringe wetlands should provide habitat and food-source support for avian aquatic life and maintain the capacity to retain sediments, immobilize nutrients, and sequester trace metals from surface waters prior to reaching the lake.

The objective of this project was to aid the development of an ecological assessment method for fringe wetlands associated with Great Salt Lake (GSL). Our goals for this assessment project were to:

i) improve wetland sampling procedures and analytical techniques to support evaluation of important biological response and stressor indicators;
ii) develop techniques to characterize good versus poor conditions across the GSL basin for a variety of physical, chemical, and biological features (including plant, aquatic macroinvertebrate, and algal communities); and
iii) develop methods to assess wetland assimilative capacity and ecological integrity for specific fringe wetland areas that receive treated effluent from adjacent wastewater treatment facilities, *with the goal of maintaining the assimilative capacity*.

1.1 Project Background

Investigation of GSL wetlands by Utah's Division of Water Quality (DWQ) began in 2004 in response to stakeholder concerns that nutrient loads from water treatment facilities adjacent to GSL may have deleterious impacts on these productive and highly valued ecosystems (CH2MHill, 2006). Initial work focused on Farmington Bay and adjacent wetlands, where wetland managers and conservation groups observed the occasional dominance of cyanobacterial mats (Miller and Hoven, 2007), a common indicator of phosphorus-induced eutrophication (Reddy and DeLaune, 2008). The concern was that these mats could negatively impact the health and vigor of desirable submerged aquatic vegetation (SAV) (e.g., sego pondweed, Stuckenia sp.), or other wetland features such as the composition of benthic macroinvertebrate communities. Both SAV and benthic macroinvertebrates are key food sources for migratory water birds (Miller and Hoven, 2007; Keddy, 2010) and important ecological components of freshwater wetlands. (See Josh Vest's work as well….)

GSL wetland classes range from marginal saltgrass-dominated meadows to extensive permanently flooded ponds (Ducks Unlimited, 2008; Emerson and Hooker, 2011), with distinct biological communities and ecosystem processes (Smith et al., 1995; Mitsch and Gosselink, 2007; Keddy, 2010) similar to those found in other large-scale wetland complexes (Albert et al., 2005; Johnston et al., 2007; Cooper et al., 2013). A large proportion of impounded wetlands adjacent to GSL are managed for waterfowl and other wetland-associated avian species by the Division of Wildlife Resources as Waterfowl Management Areas (WMAs), the United States Fish and Wildlife Service's Bear River Migratory Bird Refuge (BRMBR), and other public and private entities. Wetlands within these management areas have specifically designated water quality protections (Utah Administrative Code [UAC] R317-

2-13.9 [Link]) to support "waterfowl, shorebirds and other water-oriented wildlife . . . including necessary aquatic organisms in their food chain" (UAC R317-2-6). However, similar wetland types that occur outside the boundaries of state or federal management areas are not currently afforded specific numeric water quality protections; rather, they are protected by the narrative standards solely based on their geographic location within the lake. The development of appropriate and sensitive assessment methods for the dominant classes of GSL wetlands will support the establishment of wetland-specific water quality standards (WQS), and provide both regulatory clarity and environmental protection for Utah's Great Salt Lake ecosystem.

Fringe wetlands typically occur where freshwater flows over very gently sloping portions of the exposed lakebed. Extensive wetland areas are commonly found below freshwater sources to GSL, including outlets from impounded wetlands, wastewater treatment facility discharges, and other natural and artificial low-gradient surface channels or small streams. These wetlands are often dominated by tall emergent marsh plant communities; however, shallow open water and hemi-marsh cover types also occur. Depending on the quantity of water flow and lake elevation, fringe wetlands can span from the border of impounded wetlands to the margin of GSL itself. As such, these wetland systems are the last opportunity to immobilize, transform, or remove contaminants from surface waters prior to entering GSL.

Fringe wetlands adjacent to GSL encompass approximately 200,000 acres and are not typically managed directly by state and federal agencies, or by private hunting clubs for waterbird habitat. Fringe wetlands generally receive water that is in excess of impounded wetland requirements (or allotments). Extensive areas of marsh along GSL, including fringe wetlands as defined here, have become dominated by the invasive grass *Phragmites australis* and other monodominant marsh taxa (Kulmatiski et al., 2010; Long, 2014) that are considered undesirable by many wetland managers. Previous management efforts focused on herbicide treatment and prescribed fire to control invaded areas, however air quality issues along the Wasatch Front have necessitated a need for alternative methods. *Phragmites* control methods in development at the present time include herbicide treatment and grazing over a 5 year period to reduce surface litter and reactivate native seed banks, but the efficacy of this approach has not yet been demonstrated.

Current wetland assessment and reporting efforts are intended to support appropriate water quality standards as part of an adaptive wetland monitoring and assessment program for Great Salt Lake Wetlands. DWQ's short-term goal is to develop an assessment framework for fringe wetlands that is similar to that being refined for impounded wetlands (DWQ, 2012 and 2014). A preliminary sampling effort (2013 field season) helped refine sampling methods and generate environmental data to better understand which characteristics of fringe wetlands best represent ecosystem response to stress. An important element of this project is the development of an appropriate definition of the fringe wetland class that is suitable for probabilistic sampling designs and relevant to the health of GSL.

Fringe wetlands sampled in this project were described as predominantly emergent wetlands adjacent to GSL with shallow, fresh surface water inflows. Previous work commonly referred to these systems as "sheetflow wetlands."

1.2 Nomenclature of Great Salt Lake Fringe Wetlands

The nomenclature of "fringe wetlands" has evolved over the last ten years as research and classification schemes for wetlands of GSL have developed. Clarifying how the term "fringe wetlands" is used, and the spatial and ecological context for sites it describes, is important to understanding and interpreting previous work completed by various researchers and in framing new efforts by DWQ to assess the condition of GSL wetlands.

Efforts to characterize GSL wetlands are focused on two dominant classes of wetlands, impounded and sheetflow wetlands (defined in DWQ, 2012; DWQ, 2013). These wetland classes support a great abundance of migratory and resident waterfowl and shorebirds, and may be affected by discharges from wastewater treatment plants and other point- and nonpoint sources. As data from previous studies were evaluated, especially in the context of the surrounding landscape, the term fringe wetlands began to be used to describe nearly flat, emergent to hemi-marsh wetlands located within the transition zone between freshwater sources and hypersaline waters of GSL (DWQ 2009 and 2010). The use of the term fringe wetlands gained momentum as researchers began to more frequently use a hydrogeomorphic (HGM) approach to evaluate the function of GSL wetlands.

- Sumner et al. (2010) formally created a fringe wetlands class for GSL by consolidating four templates in the National Wetlands Inventory (NWI) functional wetland classification system into a single class—fringe wetlands. Fringe wetlands were wetlands where the GSL water elevation "maintains the water table in the wetland." Wetlands in the emergent wetlands template, by contrast, "are generally found in association with the discharge of groundwater to the land surface or sites with saturated overflow with no channel formation" (Sumner et al., 2010). It is the latter, the emergent wetlands class, where most of the original sheetflow wetland sites fall.
- Emerson and Hooker (2011) updated Sumner et al.'s (2010) classification system for Bear River Bay with the goal of simplifying and improving the interpretation of the impounded wetlands of GSL. The GSL wetland classification system includes high fringe and low fringe wetland classes that are directly linked to GSL water elevations. The emergent wetland class is associated with groundwater discharge and surface water flows. Thus, sheetflow wetland sites, under the Emerson and Hooker classification system, also fall within the emergent wetland class.

As DWQ develops an assessment framework for GSL fringe wetlands, it is important to maintain clear and consistent descriptions of targeted wetland classes that reflect project objectives. Sites targeted by DWQ's 2013 preliminary fringe wetland condition assessment specifically focus on understanding the condition of wetlands that have developed from GSL mudflats in response to freshwater surface inflow (DWQ 2013). These sites may also be influenced by groundwater and lake water elevations, but the surface freshwater inflow is considered a key feature for this class. Fringe wetland sites in this study are structurally similar to other emergent marsh wetlands described in Sumner et al. (2010) and Emerson and Hooker (2011), and sheetflow wetlands as previously (CH2MHILL, 2005; CH2MHILL, 2006; Miller and Hoven 2007) and currently described (Carling et al., 2013).

1.3 Specific Project Objectives

As touched on briefly above, a primary goal for the assessment of GSL fringe wetlands involves developing field sampling methods and analytical approaches to distinguish good versus poor condition (i.e. relative health) based on multiple ecological characteristics. These characteristics should support aquatic wildlife, such as the composition of plant, aquatic macroinvertebrate, or algal communities, while field sampling should capture a gradient of biological condition relating to key stressors or pollutants. An assessment framework for fringe wetlands would then be used to support monitoring of wetlands that are currently dominated by, and possibly dependent on, the direct discharge of treated effluent from wastewater treatment facilities. Ultimately, as the state and stakeholders gain experience and confidence applying the assessment framework, basin-wide monitoring efforts will report on the condition of fringe wetlands among watersheds in Utah's 305(b) *Integrated Report*. In addition, project-specific monitoring efforts can be developed to support compensatory mitigation requirements or water quality-based restoration projects as necessary.

The current project includes the following tasks:

(i) Develop monitoring network of FRNG wetlands along disturbance gradients. *Build on the historical collection of FRNG sites (as described in CH2MHill, 2005; 2006)*

(ii) Select (and improve) appropriate indicators of ecological condition (physical, chemical, and biological). *Preliminary literature review of potential metrics (CH2MHill, 2014)*

(iii) Develop and improve field methods for indicators (modified and updated SOPs and SAPs). *Build on previously developed SOPs (Draft documents here: Link)*

(iv) Statistical analysis of indicator data to derive responsive metrics

1.4 Wetland Assessment

Monitoring, Assessment and Reporting are essential elements of DWQ's environmental protection programs such as permitting and compliance. Similar to the efforts for streams and lakes, DWQ's Wetland program provides data on ambient conditions to support monitoring, assessment and reporting for wetlands.

For wetland assessments, there has been a distinction between efforts to evaluate wetland *condition* or *ecological integrity* (Fennessy et al., 2007; Stein et al., 2009a; Menuz et al., 2014;) as opposed to wetland *function* (Brinson, 1996; Wardrop et al., 2007; Jacobs et al., 2010). Wetland condition scores are evaluated as deviations from measured or modeled values for similarly classified wetlands that lack human alterations, or as departures from 'naturalness' (Menuz et al., 2014), while functional assessments are evaluated for specific processes or functional capacities relative to an undisturbed collection of reference standard sites (Smith et al., 1995). However, one weakness of the condition approach is that wetlands with the lowest degree of alteration (i.e. expected highest condition) do not necessarily represent the highest level of wetland functions (Hruby, 2001).

Much of the work on wetland condition is focused on emergent plant communities and development of biological indicators (*sensu* Indices of Biotic Integrity (IBI) and Floristic Quality Assessment (FQA)) that respond to landscape-scale stressors (Lemly and Gilligan, 2013; Rocchio and Crawford, 2013; Menuz et al., 2014). The central element of a plant community-based IBI or FQA is the concept of '*conservatism*' of plant species, where sensitive species have high fidelity to undisturbed conditions while other, more cosmopolitan species have a high tolerance for disturbance. In contrast, work focused on wetland functions commonly utilizes more structural attributes of wetlands (e.g. abundance of various plant strata, occurrence of alterations to a stream channel; see Jacobs et al. 2010). However, differences in variable selection between these two approaches are small. Larger differences between functional and condition assessments result from whether individual functions (or ecological attributes) are compared to reference standard sites, as opposed to similar comparisons after multiple attributes of condition have been aggregated. For example, functional assessments emphasize performance of individual functions (relative to reference standards), while condition assessments generate a more integrated view of the site that aggregates multiple functions (Stein et al., 2009b). This distinction can be important, since sites with greatest ecological condition (or integrity) may not necessarily have the highest scores for all possible wetland functions (Hruby, 2001).

A third approach to wetland assessment is conceptually derived from stream biological assessments, where various elements of biological response (e.g. metrics of community composition, indicator taxa, or multi-metric indices (MMI)) are related to both reference standard conditions and a gradient of stress (or chemical exposure) (Lougheed et al., 2007; Cvetkovic and Chow-Fraser, 2011). Work by DWQ to assess GSL wetlands relies on knowledge developed by all three approaches to wetland assessment, but our goal of ultimately developing water quality standards (WQS) for wetlands, by clarifying wetland designated uses and establishing narrative and numeric criteria to support those uses, is most closely tied to the biological assessment work.

Specifically, work by DWQ to assess FRNG wetlands relates to both (i) an assessment of ambient condition (i.e. relative health) throughout the GSL basin, as well as (ii) an assessment of whether the appropriate designated uses (e.g. aquatic wildlife (waterfowl and shorebirds)) for specific effluent-dominated sites are supported. As such, 'good condition' or 'high functioning' fringe wetlands support and maintain a robust degree of ecological complexity (as determined by comparison of biological communities against reference standard sites) and an assimilative capacity that serves to protect the designated uses of more sensitive downstream systems (as determined by changes in community composition and biogeochemical / metabolic indicators across a disturbance (or exposure) gradient).

1.4.1 Reference Standard Condition and the Disturbance Gradient

Biological assessment of aquatic resources, including wetlands, rely primarily on three key components. The first component is the development of one or more integrated measures of biological integrity; most commonly derived from the taxonomic composition of aquatic communities, such as algae (phytoplankton, periphyton or diatoms), amphibians, macroinvertebrates or plants. The second component involves the identification, characterization and classification of the resource (e.g. fringe wetlands or lacustrine marsh), including unaltered (or least disturbed) reference standard sites that can be used as the baseline for all site comparisons within a given ecosystem type. Lastly, the third component consists of an appropriate probabilistic survey design that allows for generalization of wetland health at the watershed scale (Stevens and Jensen, 2007). This report summarizes current efforts to assess fringe wetlands (component 1). DWQ is working with Utah Geological Survey (UGS) scientists on updating the classification and mapping of GSL wetlands, and is also developing a network of potential reference standard sites for both fringe and impounded wetlands with the GSL basin (component 2). A probabilistic survey (component 3) will be designed once the assessment method has been more fully developed and tested, and an appropriate and useful fringe wetland sample frame is constructed.

There are two aspects of assessment for GSL wetlands that complicate the process of methods development. First, wetlands associated with GSL have been intensively managed, and even created, for a variety of purposes (uses) over the last century. These wetlands have received a wide range of sediment, nutrient and other pollutant loads from agricultural, urban and industrial sources as the eastern shore of GSL became more developed. As such, there is no *a priori* set of reference standard sites that represent the highest degree of ecological integrity (*sensu* Stoddard et al., 2006) adjacent to GSL for comparison. DWQ is working to identify potential reference standard wetlands farther afield, away from specific activities or discharges that may have degraded wetlands within the GSL assessment area. Two areas have been identified where wetlands are likely to have received a lower level of historic and contemporary disturbances; wetlands associated with Fish Springs National Wildlife Refuge (NWR), and wetlands within Snake Valley (a remote area of Utah's West Desert). Both areas are within the historic extent of Lake Bonneville, have broadly similar plant communities, and contain a similar range of water salinity as wetlands more closely associated with Great Salt Lake. Field sampling is on-going (2014-2016) to capture the range of natural variability of these systems. Results from this work will be incorporated into assessments for both fringe and impounded wetlands.

A second complication results from the significant degree of hydrologic modification found within the eastern portion of the Great Salt Lake basin. Water is routinely scarce in Utah, and a vast and complicated system to manage water quantity, involving ditches, drains, canals and dikes, is used to distribute surface and pumped groundwater to and from irrigated agricultural users, historical and contemporary industrial sites, and ultimately to GSL wetlands (CH2MHill, 2012). Most efforts to quantify (or characterize) disturbance or stressor gradients for wetlands rely on landscape-scale measurements (e.g. cover of various land use classes, road density), or build on some form of best professional judgment to classify wetland stress/disturbance. By contrast, site-scale effects derived from distinct water sources (with distinct types and concentrations of point and non-point source pollutants) are likely to be particularly important to the more sensitive aquatic portions of GSL wetlands. As such, landscape-scale measurements of stress may fail to capture the response of biological indicators attributable to water quality. DWQ is working with UGS to integrate spatial data on wetland locations (e.g. impounded wetland boundaries) with recently acquired high-resolution digital elevation data and surface water networks to better understand the quantity and quality of water flows to GSL wetlands.

1.5 Framework for Fringe Wetland Assessment

This project involved the targeted selection and sampling of fringe wetlands associated with Great Salt Lake. Field work was performed in 2013 and 2015. Key measures of biological response were plant and aquatic macroinvertebrate community composition. Due to the strong hydrologic element of this wetland type, measurements were made along transects perpendicular to flow at three distances (100, 300 and 500 m) from water inflow to the wetland. Water chemistry samples were collected from the main channel (or flowpath) at each distance and analyzed for a variety of conventional water quality parameters, as well as total nutrients and metals. Macroinvertebrate were collected from inundated areas within and adjacent to the main flowpath, for each distance from the inflow (3 to 10 composite samples per site). Plant community composition was measured along the six (6) 50 m perpendicular transects, two opposing transects at each distance from the inflow. Samples of wetland soils were collected adjacent to the main flowpath and at the end of each perpendicular transect (9 samples per site), for analysis of nutrient and metal concentrations.

This report summarizes key results from sample collections, and represents a preliminary effort to identify meaningful and responsive metrics of the relative health (i.e. condition) of this wetland class. Continuing work will refine these metrics and identify potential stressor-response patterns protective of both fringe wetlands and associated downstream uses. DWQ's goal is to identify appropriate biological and ecological characteristics that can be used to refine (or establish) numeric criteria and develop assessment methods for narrative standards that are appropriately protective to people and wetland biota. Once established, DWQ can assess the chemical and physical conditions that are most strongly associated with healthy versus degraded wetlands, which ultimately can be used to define water quality goals that are specific to these ecosystems.

2.0 Methods

2.1 Study Area

The updated National Wetlands Inventory (NWI, 2008) estimated approximately 173,000 hectares (427,000 acres) of wetlands along Great Salt Lake (see Figure 1). These wetlands serve as vital habitat for millions of migratory shorebirds, waterfowl, and other wildlife. In addition, these wetlands provide essential ecosystem services, including moderation of surface water and groundwater flows, and removal of nutrients and other pollutants. There continues to be an essential need to maintain the health and extent of these ecologically critical wetlands, especially in the face of severe and persistent threats from (Millennium Ecosystem Assessment, 2005; Dahl, 2006):

- population growth (the majority of Utah's citizens reside within the GSL watershed)
- industrial and urban development
- excessive surface water and groundwater withdrawal
- establishment and dominance of invasive species
- high rates of nutrient loading

Protecting and maintaining the health of these ecosystems requires scientifically defensible and quantitative measures of wetland condition.

2.1.1 Geography

This project largely takes place in fringe wetlands surrounding the Great Salt Lake, Utah, HUC Sub-region 1602, however additional sites from remote areas of Utah's West Desert (HUC 16020601 and 16020603) are included as potential reference standard sites. The project area includes portions of Salt Lake, Box Elder, Weber, Davis, and

Tooele (and Juab or Millard) counties. GSL fringe wetlands are located above the elevation of GSL and below 4,218 feet above sea level, while West Desert reference sites may range in elevation from 4304' to over 4800' .

2.1.2 Ecological Context

Fringe wetlands occur where freshwater flows over very gently sloping portions of exposed soil or sediments within the GSL basin. Fringe wetlands are commonly found below the outlets from impounded wetlands, wastewater treatment facilities, and other low-gradient surface channels or small streams. Although less common, this wetland type may also be encountered below areas of groundwater discharge, such as springs or seeps.

Most GSL sediments contain substantial quantities of salt, and the salinity of both GSL water and sediments restricts the growth of emergent vegetation. Flow of freshwater over sediments of fringe wetlands can flush enough salts out to support various emergent marsh species, including luxurious growth of bulrush (Scirpus spp.), cattail (Typha spp.), and others. Depending on the quantity of water flow, wetland geomorphic features, and lake elevation, fringe wetlands can extend from the border of impounded wetlands to nearly the margin of GSL itself. Longer-term variation in lake elevation (on the order of decades) can "reset" the dominant vegetation of these wetlands by the intrusion of highly saline lake water into the wetland during high-water years. Plants appear to rapidly recolonize fringe wetland areas once lake levels decline and fresh surface water flows or precipitation reduce soil salt content below some, currently unknown, threshold. Many fringe wetlands contain a variety of plant species with variable sensitivity to salt stress and wide gradients in soil and water salinity.

The principal source of water to fringe wetlands is from surface water delivered via extensive networks of impounded wetland outfalls, canals, ditches, and streams. The relative importance of terrestrial vs. aquatic features within these wetlands can change markedly from year to year and across the growing season.

Three important measurement parameters of fringe wetland assessment are plant and macroinvertebrate community composition, including the cover of native and exotic vegetation; water chemistry; and soil chemistry, including analyses of salinity, nutrients, and metals. Water depth appears to exert a strong influence of these parameters, above and beyond any potential effects of water quality, per se. As such, specific efforts were made during site reconnaissance to identify the dominant flow pathways within each wetland where water depths are adequate for sampling. Sampling locations within a given site were at least 50 m from an adjacent dike or shoreline and roughly 100, 300, and 500 m from any water source. These sampling restrictions allowed the field crew to collect data from central portions of the wetland along the major flow pathway, where water chemistry is expected to be most representative of ambient hydrologic conditions.

2.1.3 Land Cover

Fringe wetlands surrounding GSL encompass approximately 80,000 hectares (200,000 acres) and are not typically managed actively by State and Federal agencies for waterfowl habitat. Three main basins contribute the vast majority of surface water to GSL (Arnow, 1984), the Bear River, Weber/Ogden Rivers, and the Jordan River. Menuz et al. (2014) summarized some baseline land cover characteristics of these basins (see Table 1 below) in a recent report on the condition of GSL emergent wetlands.

Table 1. Land cover of major drainage basins contributing to GSL and associated wetlands

Drainage Basin	Area (km^2)	% Open Water	% Wetland	% Woody	% Grazable	% Cultivated	% Developed
Bear	19,463	2.5	3.2	67.6	15.7	8.7	2.3
Jordan	9195	5.0	1.8	67.9	10.7	2.7	11.9
Weber	6436	2.5	2.5	78.3	7.7	1.6	7.2
West Desert	14,177	0.4	2.2	78.1	3.0	0	0.4

Adapted from Menuz et al. (2014).

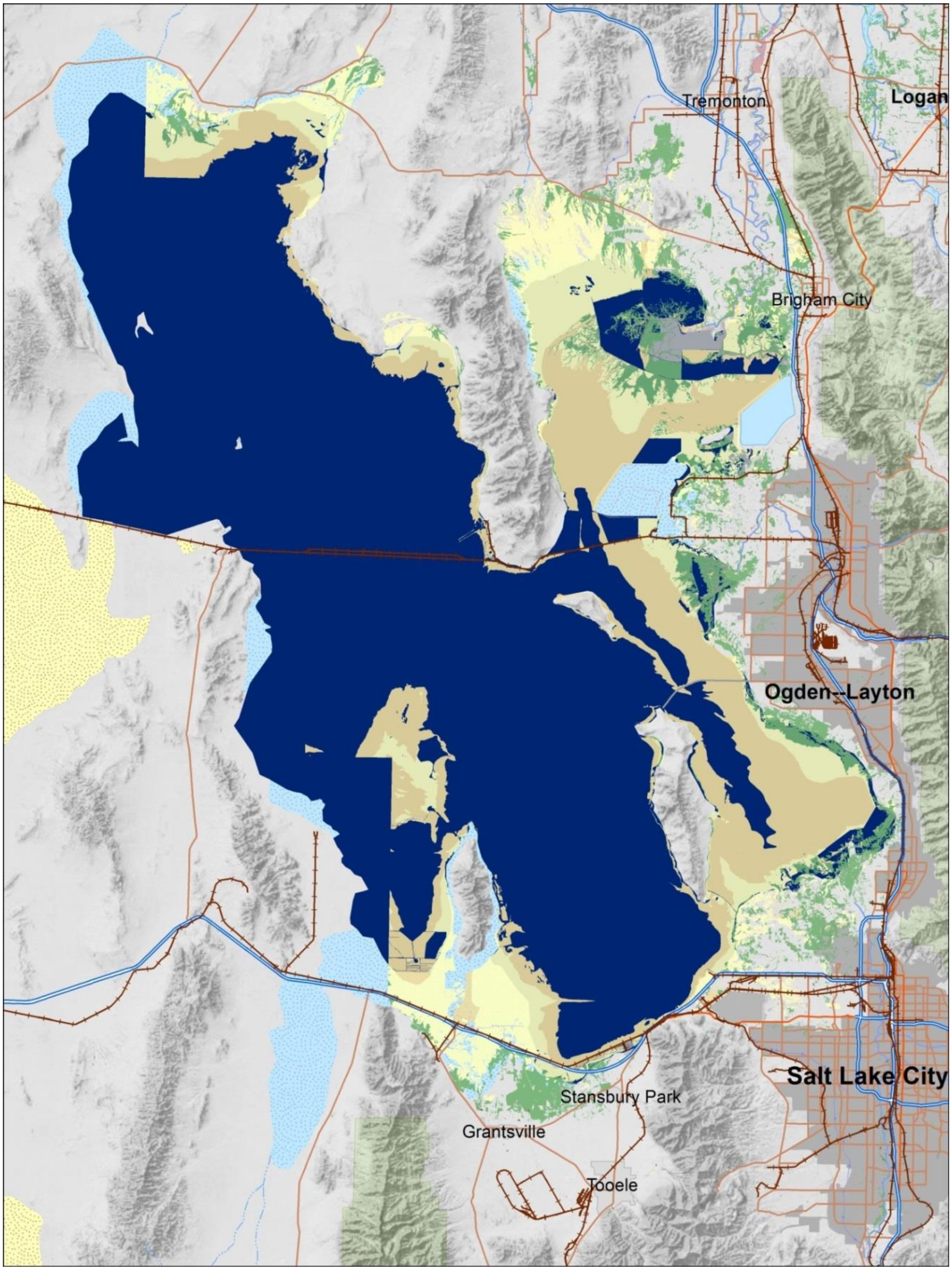

Figure 1. Major wetland classes associated with Great Salt Lake.

2.2 Site Selection

Sites were selected from GSL fringe wetlands having a defined freshwater source flowing across the site. Because this is a preliminary survey, a targeted selection of high- and low-quality wetlands was used as a first step to compare the ability of various metrics to discern good vs. poor condition (i.e. responsiveness). In an effort to account for a wide range of fringe wetland characteristics, the following categories were developed as part of a desktop evaluation of study sites to clarify potential sources of among-site variation: Historical Sampling Sites, Upstream Water Source, Watershed, and Morphology. A goal of this effort is to identify and characterize potential covariates that may influence wetland condition. Figure 2 illustrates the approximate location of potential sampling sites.

2.2.1 Historical Sampling Sites

Several fringe wetlands sites were examined in the initial 2004–2006 studies completed by DWQ (CH2M HILL, 2005 and 2006; Miller and Hoven, 2007). Including these sites provided an opportunity of how sites may have changed over time. These sites are located at Public Shooting Grounds Waterfowl Management Area, Kays Creek, Central Davis Sewer District's outfall, North Davis Sewer District's outfall, and Farmington Bay Waterfowl Management Area (see Table 2 below).

Table 2. Proposed Fringe Wetland Sites

Site ID *	Site Name	Historic Site	Water Source	Location	Morphology	Previously Sampled?
PSGWMA-WLO	PSG – Widgeon Lake Outfall	Yes	Impoundment	Bear River Bay	Diffuse	No
PSGWMA-HLO	PSG – Hull Lake Outfall	No	Impoundment	Bear River Bay	Point Source	No
PROM-01	Promontory Range Springs – 01	No	Groundwater	Bear River Bay	Groundwater	Yes
PROM-02	Promontory Range Springs – 02	No	Groundwater	Bear River Bay	Groundwater	No
Bear-U2D	BRMBR – Unit 2D Outfall	No	Impoundment	Bear River Bay	Diffuse	Yes
BRMBR-U3E	BRMBR – Unit 3E Outfall	No	Impoundment	Bear River Bay	Diffuse	No
HCWMA-BPDR	Harold Crane WMA Bypass Drain	No	Channel	Bear River Bay	Point source	No
HC-East	Harold Crane WMA Off East Pond	No	Impoundment	Bear River Bay	Diffuse	Yes
OBWMA-U1	Ogden Bay WMA Unit 1 Outlet	No	Impoundment	Gilbert Bay	Diffuse	No
OBWMA-WR	Ogden Bay WMA Weber R. Outfall	No	Channel	Gilbert Bay	Point Source	No
HSWMA-NUO	HSWMA North Unit Outlet	No	Impoundment	Gilbert Bay	Point Source	No
HSWMA-SO	HSWMA South Outlet	No	Impoundment	Gilbert Bay	Point Source	No
NDSD	North Davis Sewer District	Yes	UPDES	Farmington Bay	Point source	Yes
TNC-KC	The Nature Conservancy Kays Creek	Yes	Channel	Farmington Bay	Point source	Yes
CDSD	Central Davis Sewer District	Yes	UPDES	Farmington Bay	Point source	Yes [2]*
FBWMA-U1	FBWMA - Unit 1 Outlet	Yes	Impoundment	Farmington Bay	Point source	No
FBWMA-TRPN	FBWMA - Turpin Unit Outlet	Yes	Impoundment	Farmington Bay	Point source	No
FB-SERP	FBWMA - Unit 2 Foremarsh	No	Impoundment	Farmington Bay	Diffuse	Yes
NWOD	NW Oil Drain Outfall	No	Channel	Farmington Bay	Point source	No
ADCO	Ambassador Duck Club Outfall	No	Impoundment	Farmington Bay	Point source	Yes
GOGGDR	Goggin Drain Outfall	No	Channel	Gilbert Bay	Point source	Yes

NOTES: * Two sites were sampled at Central Davis SD. UPDES = Utah Pollutant Discharge Elimination System; PSG = Public Shooting Grounds Waterfowl Management Area; BRMBR = Bear River Migratory Bird Refuge (USFWS); FBWMA = Farmington Bay Waterfowl Management Area; HSWMA = Howard Slough Waterfowl Management Area;

As described briefly in DWQ's preliminary report on the 2013 Fringe Wetland Survey (DWQ, 2014), it was difficult to directly compare sites sampled in 2013 against the historical sites, due to differences in sample location within wetlands and the rapid change vegetation and salinity resulting from localized changes in hydrology and lake levels.

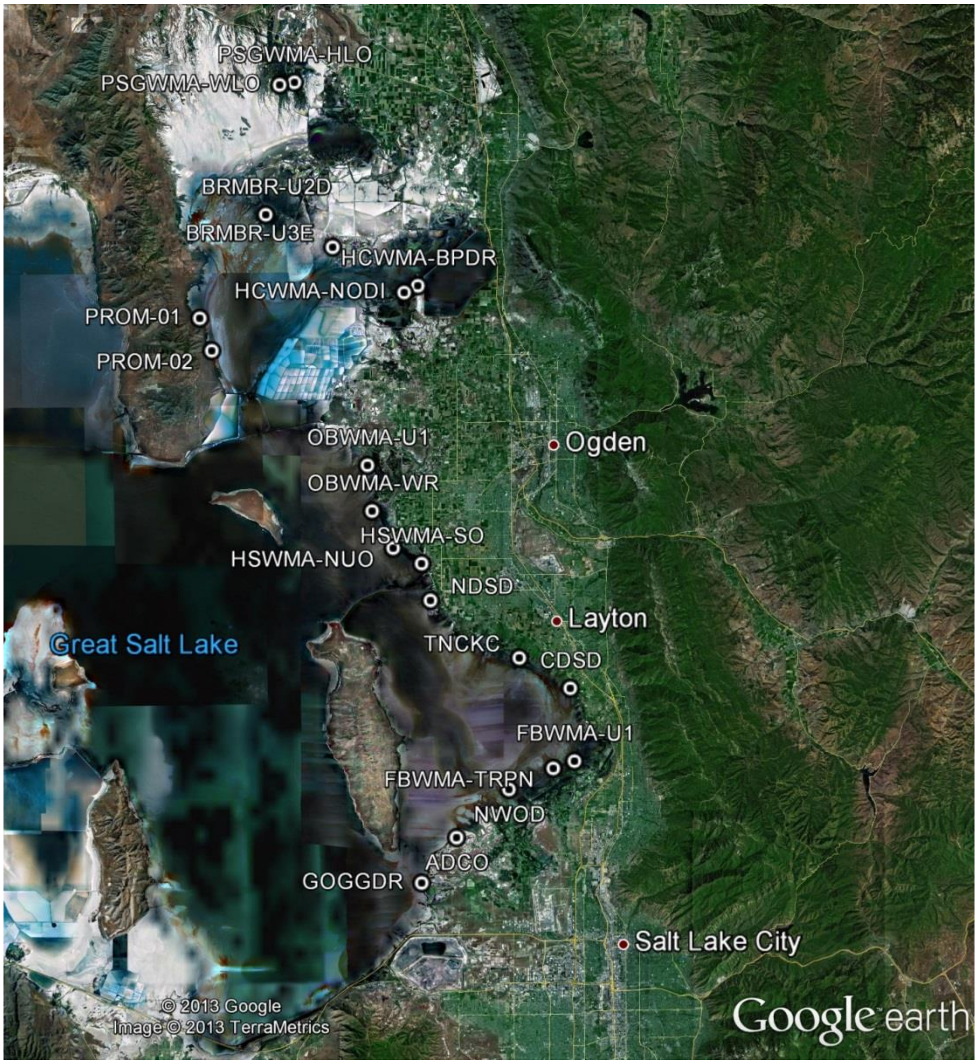

Figure 2. Map of proposed fringe wetland sites

2.2.2 Upstream Water Source

This category attempts to account for potential differences in upstream water quality as influenced by distinct types of water sources, as well as hydrologic characteristics of each site. The different upstream water sources include (1) wastewater treatment plants (a point source), (2) creek/irrigation return flow (a nonpoint source in terms of potential contaminants but contributing to the wetland as a point source), (3) groundwater source, and (4) an impoundment (water from point and nonpoint sources has been detained/integrated prior to entering the fringe wetland).

2.2.3 Watershed

The main hydrologic units (HUC-8 subbasins) providing inflow to these wetlands. The subbasins contribute to distinct bays within GSL that vary in lake salinity. Depending on where the fringe site is located, it could be influenced by GSL waters with a wide range of salinity. These locations include (1) Farmington Bay, (2) Bear River Bay, and (3) West Desert. *One site is located within the Gilbert Bay portion of GSL, but all inflows result from Farmington Bay water sources, and the site was recoded as belonging to the Farmington Bay watershed.*

2.2.4 Geomorphology

This category characterizes the influence of local geography on the geomorphology of fringe wetland, including how water enters and flows across the wetland. This category is subdivided into the following: (1) converging site (a dike or pond distributes water over wide area, water flows across mudflat and converges to single channel), (2) diverging site (water starts at a point source, typically a single channel and braids/spreads across mudflat), and (3) groundwater source.

2.2.5 Evaluation of Potential Sampling Sites

The sampling period for this project was July through August, 2013. DWQ evaluated potential sampling sites to confirm selection criteria were met. DWQ's objective was to sample 15 sites in 2013. Criteria to evaluate potential sampling sites include the following:

- Target/Nontarget: *Does the site represent a fringe wetland (> 2 hectares or 5 acres) that is adjacent to GSL and receives freshwater inflow?*
- Permission/Access: *Has explicit permission to access the site been obtained from the landowner?*
- Sampleable: *Can site be sampled during the sampling index period?*
- Representation: *If there is an adequate number of available sites, do the available sites provide an adequate representation for each of the categories listed in* Table 5*?*

2.3 Field Methods

Each wetland was sampled using a frame as shown in Figure 3 and Figure 4. This sampling frame is designed to allow comparison among fringe wetland sites at a similar scale; therefore, the size and length of transects have been standardized. The beginning of the sampling frame (i.e., 0 m distance) is the point where:

- an open channel enters the lakeshore;
- the end of pipe or weir contributes flow to the wetland;
- the downstream edge of a dike with multiple weirs discharges to the wetland;
- groundwater discharges from a spring, located below the transition from upland to lakeshore; or
- water flow crosses a major change in wetland structure (e.g. shift in plant community from tall emergent marsh to hemi-marsh).

If the end of pipe, weir, or groundwater spring is located upstream of the transition from upland to lakeshore, then the beginning of the sampling frame may be located where the resulting flow breaches the transition from upland to lakeshore.

The fringe wetland class, as defined in this document, contains a wide range of both aquatic and terrestrial features. As such, the sampling layout for this preliminary survey will include measurements from both open water and emergent components of this ecosystem type. The open water, or aquatic, elements of the sampling layout are dependent on identifying the predominant flow path based on desktop-based geographic information system (GIS) reconnaissance and field inspection at each site.

Since these wetlands can range in size from approximately 10 to over 1,500 hectares, initial aquatic environmental data collections occurred at three locations representing 10 percent, 50 percent, and 90 percent of the flow path length. However, due to the size of some of the wetland sites, and great difficulty traversing such distances through dense emergent marsh (primarily stands of *Phragmites australis*), flow path lengths were capped at 500 m in this project. **As such, transects were placed 100, 300, and 500 m from where surface water enters the**

wetland. Water chemistry, sediment chemistry, leaf nutrient, and benthic macroinvertebrate samples were collected at each of these locations, as described below.

The emergent, or terrestrial, elements of the sampling layout were based on two 50 m transects oriented perpendicular to the flow line at 100, 300, and 500 m along the flowpath. Vegetation cover, including emergent and floating aquatic plants as well as algal mats, was estimated visually along a 1 m-wide belt for each transect. Vegetation transects were broken up into 10-m segments due to the dense nature of marsh vegetation within this wetland type. At the terminus of each transect, samples were collected for sediment (soil) and leaf chemistry, and benthic macroinvertebrates community composition.

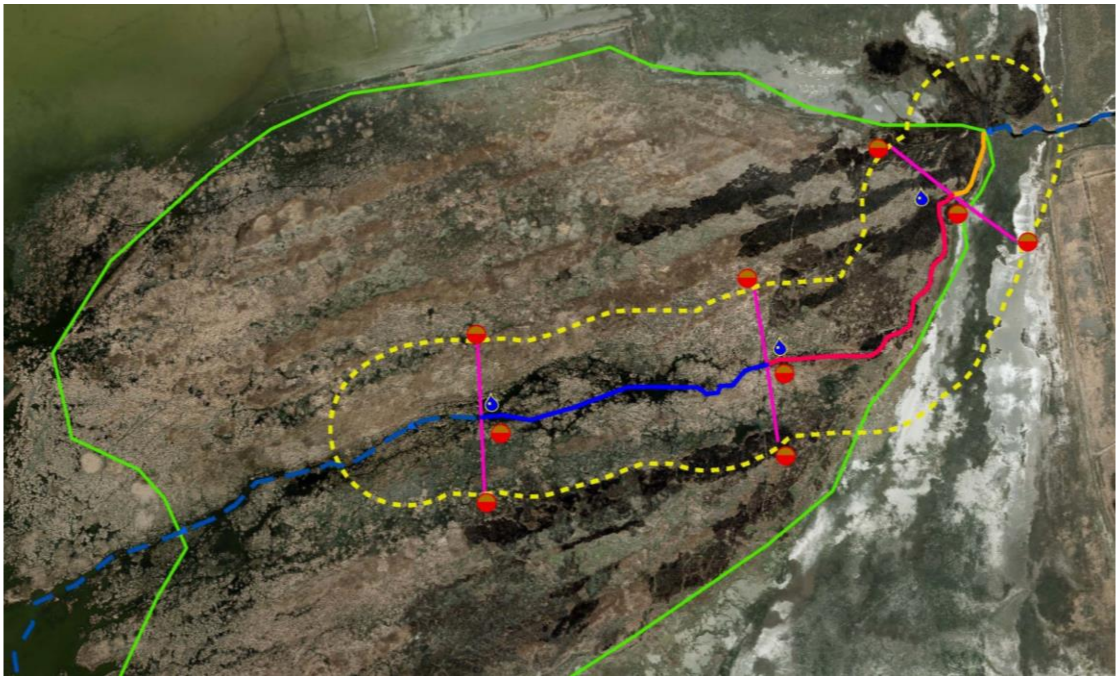

Figure 3. Sample collection frame for fringe wetlands.

Major sample collections include:

Vegetation composition and cover observations were collected to characterize aboveground attributes of fringe wetland sites, particularly the physical structure of various wetland habitats and the relative dominance of exotic or invasive plant species.

Benthic macroinvertebrate community composition observations were collected to characterize the benthic community, which is an important food source for higher trophic levels (waterfowl, shorebirds, etc.) and also plays an important role in nutrient and organic matter cycling in aquatic wetland habitats.

Water chemistry (nutrients, major ions, and metals) data were collected to characterize the basic constituents available as building blocks for vegetation, macroinvertebrates, and other biological processes.

Supplemental indicators include the following:

Sediment extractable nutrients and metals data were collected to help determine if historical inputs to wetlands may have deposited nutrients, such as P, or toxic contaminants, such as Hg, that may continue to affect the condition of the wetlands.

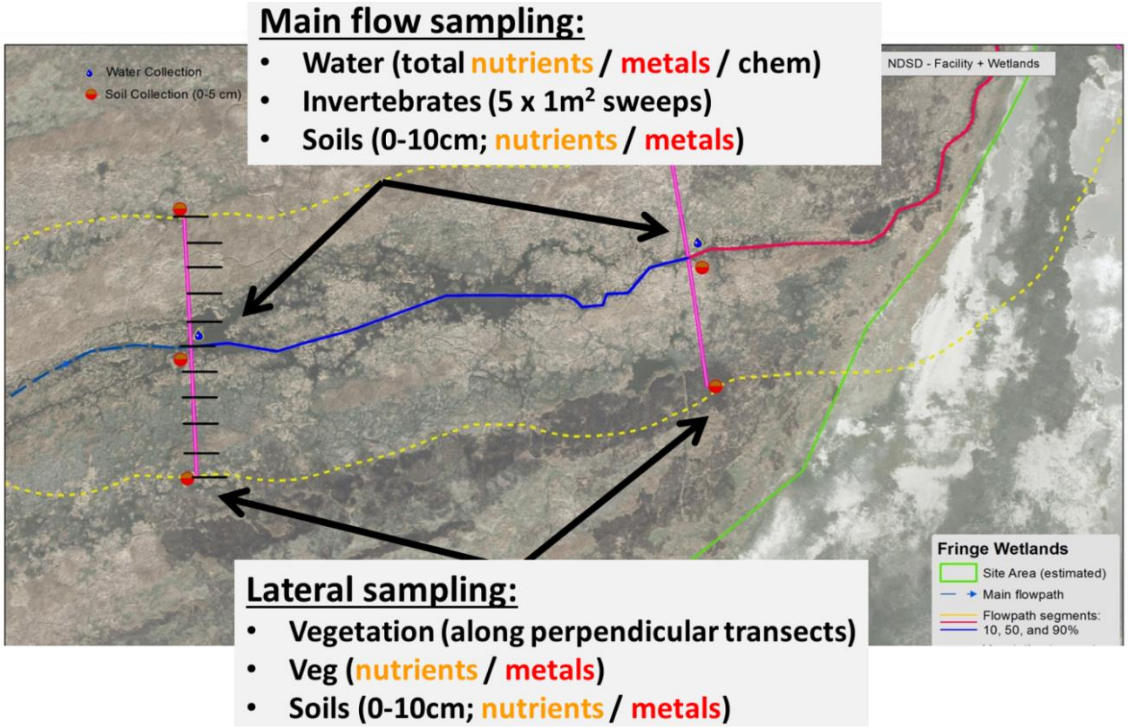

Figure 4. Location of water, invertebrate, soil, and vegetation sample collection within the sample frame.

Leaf CNP concentrations and $\delta^{15}N$ isotope ratios of dominant emergent plant species were collected to assess the potential sources of nutrients for plant growth.

These parameters were measured at all sites. A brief description of each measured parameter is found in Table 3.

2.3.1 Environmental Sampling – Water Chemistry

Water chemistry sampling involves two separate activities, as shown in Table 3. Field parameters were measured using a multi-parameter probe (Hydrolab or similar). This is typically one of the first activities performed during a site visit. Procedures for (daily) calibration and use of the multi-parameter probe are provided in SOPs on DWQ's Wetland Program '*Monitoring and Assessment*' web page (Link)[1]. This project used the temperature, specific conductance, pH, and DO probes. Multi-parameter probe data was recorded on field sheets once the results had been verified as acceptable by the field crew and stored on the instrument; field sheets also included any notes about site conditions observed during the measurement.

The second sampling component is the collection of water samples for chemical analysis. This was also typically one of the first activities performed during a site visit. Specific procedures for collection of water grab samples are described in the SOP (Link). Several volumes of surface water were collected for six different types of analysis. Five bottles were filled for Total Nutrients, General Chemistry, Total Metals, Sulfide, and BOD5. One or more "transfer bottles" were filled and filtered for Chlorophyll-α analysis (Link). Both multi-parameter measurements and field water samples (bottles) were collected at 100, 300, and 500 m along each flow path segment. *In 2015, the sampling approach was modified to include water chemistry samples from 0 m distance.*

[1] SOPs and Sampling and Analysis Plans for DWQ's wetland assessment work can be accessed at: www.deq.utah.gov/Programs Services/programs/water/wetlands/monitoring.htm.

Table 3. Measured Parameters

Description		Field Method*	Details
Vegetation		Visual Observation	1 m wide by 100 m belt-transects perpendicular to main flow path at 10%, 50%, and 90% of path length (up to 500 m); total of three transects per site Vegetation species composition and % cover Cover of Filamentous Algae and Floating Aquatic Vegetation *** No samples were collected, visual observation only*
		Leaf Harvest	Five leaves from dominant plant species at each sampling location; sample mature leaf (fully expanded leaf 1-3 nodes below the top of plant, or the top 30 centimeters of culm (for Schoenoplectus spp.). *** One gallon-size zip bag ** Sent to USU Isotope Lab*
Benthic Macroinvertebrates		Sample Collection using Stovepipe	Five stovepipe collections within dominant flow path, and outside end of each 100 m perpendicular transect (transects composited per perpendicular transect at 10%, 50%, and 90%) *** Two wide-mouth polyethylene quart jars at each sample location ** Sent to Gray Lab*
Water Chemistry	Field Parameters	Multi-Parameter Probe	Temperature, Specific Conductance, pH, Dissolved Oxygen
	General Chemistry	Grab Sample Collection	Alkalinity, Total Suspended Solids, Total Volatile Solids, Total Dissolved Solids, Sulfate ($SO_4^{=}$), Hardness *** One 1000 mL bottle ** Sent to State Water Lab*
	Total (unfiltered) Nutrients	Grab Sample Collection	NH_4^+, NO_3^-/NO_2^-, Total Kjeldahl Nitrogen (TKN), Total P, DOC *** One 500 mL bottle with H_2SO_4 preservative ** Sent to State Water Lab*
	Total (unfiltered) Metals	Grab Sample Collection	Aluminum, Arsenic, Barium, Cadmium, Cobalt, Copper, Iron, Mercury, Manganese, Nickel, Lead, Selenium, Zinc *** One 250 mL bottle, preserved with HNO_3 ** Sent to State Water Lab*
	Sulfide	Grab Sample Collection	Hydrogen sulfide as total sulfide *** One 120 mL bottle with ZnoAc and NaOH preservative ** Sent to State Water Lab*
	Chlorophyll-a	Grab Sample Collection and Field Filtering	0.7-µm filter residue *Sent to State Water Lab*
Sediments	Extractable nutrients	Sample Collection using a Corer	Separate 0-10 cm cores at endpoints and center of vegetation transects (Nutrient Extracts: NH_4, NO_3/NO_2, PO_4); Total N, Total P and Organic C *** Stored in separate 1-gallon zip bags ** Sent to USU Stable Isotope Lab*
	Acid-soluble metals	Sample Collection using a Corer	Composite of 0-10 cm cores (collect half of each sediment-nutrient core and composite) for each perpendicular transect Aluminum, Arsenic, Barium, Cadmium, Cobalt, Copper, Iron, Mercury, Manganese, Nickel, Lead, Selenium, and Zinc *** Stored in three separate 1-gallon zip bag** Sent to UU ICP-MS Lab*

2.3.2 Environmental Sampling – Vegetation

Emergent vegetation and ground cover was sampled by visual estimation of aerial cover within a 1-m band along each perpendicular transect at each distance from the inflow to the wetland. Each transect was broken up into 10- or 20 m segments to facilitate species identification and cover measurements in thick marsh vegetation. These data, along with other pertinent observations, such as cover of algal mats or evidence of soil disturbance, were recorded on a field sheet (Link).

2.3.3 Environmental Sampling – Macroinvertebrates

Benthic macroinvertebrates were collected from undisturbed and representative areas within the open water flow path, and inundated areas adjacent to the flow path at 100, 300, and 500 m distances from water inflow. Samples were obtained by a series of three to five 'D-net' (500 µm mesh) 'sweeps' along a swath approximately 30 cm wide by 100 cm long. In dense vegetation, efforts were made to clear much of the upper portions of aboveground biomass from the area without overly disturbing the surface soil prior to a sweep. Vegetation, detritus, and surface soil materials were commonly included in the sample so that invertebrates adhering to these materials were not discarded; these materials were removed in the laboratory during sample identification and enumeration. Samples were composited for each sampling location (k=3 per site). Procedures are described in the SOP (Link).

2.3.4 Environmental Sampling – Soils

Sediment available nutrients and total metals were sampled from an undisturbed area within the open water flow path and at the end of each vegetation transect for all three sample locations (100, 300, and 500 m distances). Briefly, the goal was to collect the top 10 centimeters of loose sediment (or mucky soil) from 5-cm diameter cores. The 0- to 10-centimeter core was split longitudinally in the field, using a soil spatula, and each half of the core placed in separate 1-gallon sample bags. One-half of the core was placed in a labeled bag for nutrients; the other half of the core was placed in another labeled bag for acid-soluble metals. Nine samples were collected per site (3 locations per transect distance x 3 distances) for both nutrient and metals samples (Link).

2.4 Laboratory Methods

All chemical analyses were performed in accordance with standard laboratory methods by the contracted laboratories. Specific details for each method and laboratory are located in the project SAP (DWQ, 2013).

2.5 Data Quality Objectives

Data quality objectives are qualitative and quantitative statements derived from systematic planning that clarify the study objective, determine the most appropriate types of data to collect, determine the most appropriate conditions from which to collect data, and specify the level of uncertainty allowed in the collected monitoring data while still meeting project objectives (EPA, 2006). Project specific information is summarized in Table 4 below.

Table 4. Data Quality Objectives

Step	DQOs for 2013 Great Salt Lake Fringe Wetland Targeted Survey
Problem Statement	Wetland resource managers and engaged stakeholders had previously observed algal mats within GSL wetlands and expressed concern that this could be an indicator of poor wetland health resulting from high N and P loading from wastewater treatment facilities, possibly impacting the food sources of waterfowl and shorebirds using these areas. It was suspected that wetlands with high nutrient loads may not be supporting their beneficial use of waterfowl habitat and necessary food chain. In response, DWQ initiated the development of a framework to assess the relative condition of impounded and fringe wetlands of GSL. The assessment framework for impounded wetlands has been refined and now awaits further testing. This project represents the initial data collection effort for fringe wetlands to inform a preliminary MMI, based on wetland condition / integrity.
Goal of Study / Decision Statements	*<u>Key Question[s]</u>* Q0: What key variables define the function, structure, and condition of GSL fringe wetlands? Q1: What stressors are impacting the condition of GSL's fringe wetlands? Q2: What metrics are most useful for evaluating wetland condition and stress with respect to beneficial use classes? *<u>Potential Outcomes</u>* 1: Information is adequate to answer the key questions, resulting in a preliminary MMI for fringe wetlands to be shared with wetland managers and stakeholders, and subsequently validated using a probabilistic survey. 2: Information is inadequate to develop robust metrics of relative condition of fringe wetlands. DWQ will identify potential confounding factors, develop appropriate sampling and analytical methods, revise the sampling plan, and complete reporting as above.
Inputs to Decision	The following information was collected: Field sampling, included collection of water chemistry and biota samples, was conducted one time during the 2013 growing season (midsummer) at 10 selected sites adjacent to GSL. *<u>Water chemistry parameters</u>*: Total nutrients, total metals, chlorophyll a, general chemistry (major ions, suspended solids), and field measures (DO, temp, pH, salinity) using appropriate and documented methods. *<u>Benthic macroinvertebrates</u>*: Species composition of benthic macroinvertebrate communities using appropriate and documented methods. *<u>Field measures of vegetation and surface mat</u>* cover were collected using appropriate & documented methods. *<u>Sediment metals and nutrient availability</u>*: Total (digested) metals and exchangeable nutrient concentrations using appropriate & documented methods. *<u>Field observations of stressors</u>*, including soil and vegetation disturbance, altered hydrology, over grazing, and the establishment and dominance of invasive plant species. <u>Supplemental Indicators</u> may be collected. These include: Leaf C, N, and P concentration, and δ15N and δ13C isotope ratios from dominant emergent plants along transect endpoints and open water sampling locations. This information is described in Section 2.3and Table 3.
Study Boundaries	The study area for this project includes fringe wetlands within Farmington Bay, Ogden Bay, Bear River Bay, and Gilbert Bay portions of Great Salt Lake. Spatial data identifying fringe wetlands is derived from reclassified National Wetland Inventory data and other sources as available. Sampling sites were field-checked to ensure that they: *Represent the sample target*—Fringe wetlands associated with and adjacent to the GSL *Are accessible*—DWQ has received permission to visit wetlands on private property Weather is a major constraint for all sampling and monitoring activities because storms can limit access to field sites and the ability to safely conduct sampling and measurement activities at the study area. GSL levels and private property access may be a constraint and affect sampling locations. Ownership information and permission was obtained as early in the study as possible.

Step	DQOs for 2013 Great Salt Lake Fringe Wetland Targeted Survey
Decision Rules	If information is adequate to answer the key questions, then DWQ will present results and recommendations in a final report. If information is inadequate to answer the key questions; DWQ will identify potential confounding factors, develop appropriate sampling and analytical methods, revise the sampling plan, and complete reporting as above.
Acceptance Criteria	PARCC elements for data *Precision*—Because of the difficulty obtaining sufficient sampling sites, field replicates were not collected. *Accuracy*—Special efforts were made to minimize contamination of water chemistry samples through proper collection of field samples and use of appropriate laboratories for analysis. Field surveys were performed by a monitoring crew trained in each method. Few species of vegetation occur within the project area and are generally easily identified, but questionable specimens were collected and returned to the office for further identification. Taxonomic identification of macroinvertebrates was performed by Dr. Larry Gray (Utah Valley University). *Representativeness*—The sampling locations have been selected based on a review of aerial photos, and sites were chosen due to their landscape scale characteristics. Sites were chosen to encompass potentially unique characteristics of different conditions, such as water source, potential salinity impacts, and morphology. Inventory methods were designed to collect data at a scale most descriptive of GSL wetlands (~ 50 hectares). Site photos and field notes were collected at each site to describe any unusual conditions that may occur. *Completeness*—To ensure the sampling goal of 100 percent completeness at the end of the season, we will use field reconnaissance to verify that sites have the proper hydrologic conditions to support fringe wetlands. *Comparability*—All field sampling and analytical procedures were completed following both previously tested and newly developed SOPs for each metric and were performed by the same field crew throughout the sampling season. Measurement quality objectives for chemical measurements are specified in the SAP (DWQ, 2014). DWQ QAPP specifies the minimum QA/QC objectives for sample measurement.
Sampling Plan and Design	The baseline sampling program includes the following: Collection and analysis of water, macroinvertebrates, and surface sediments for chemical, physical, and taxonomic attributes, as appropriate Field observations of vegetation and algal mat cover Data were used to estimate baseline conditions of fringe wetlands associated with GSL. Forthcoming analyses will use data to construct MMIs for key indicators, such as Water Chemistry, Benthic Macroinvertebrates, Vegetation, and Sediment Chemistry, following reasonable and convincing linkage to beneficial use of these wetlands, via examination of relationships among wetland physical, chemical, and biological condition; other indicators may be developed as appropriate.

3.0 Data Analysis

The dynamic nature of the Great Salt Lake basin, coupled with a long history of industrial, agricultural and municipal impacts to GSL and its surrounding wetlands, has resulted in a very complex set of hydrologic, chemical and biotic stresses to fringe wetland ecosystems. The initial focus of this project was to identify key variables that characterize the function, structure, and condition (i.e. relative health) of GSL fringe wetlands in response to a wide range of potential stressors (Table 4). Current work explores patterns in the taxonomic composition of emergent plant and benthic macroinvertebrate communities in response to field measurements of land cover, physical conditions at the air-water-soil interface, and water and soil chemistry. Over the course of two sampling years (2013 and 2015) 28 sites were sampled from a variety of fringe wetland areas.

While data were collected from a variety of spatial scales, results presented here were mainly aggregated for each site. Taxa lists were developed for plant and macroinvertebrate communities and organized into preliminary databases to support comparisons with local and regional literature and expertise. The structure of the plant and macroinvertebrate databases is still being developed, largely in collaboration with others working on other GSL wetland types, but currently includes information on plant wetland indicator status (hydrophytic vegetation), physiognomy and 'C-values' (coefficients of conservatism; see Menuz et al. 2014), as well as taxonomic classification, taxon codes and lowest taxonomic units (LTUs), and feeding group and common-language descriptions of organisms (e.g. diving beetle, biting midge, and flatworms). These databases are being supplemented with information from other wetland classes as well as historical data collections.

Overall, the structure of sample data analyzed for this project involve three samples within each site, located at 100, 300 and 500 m (*transects*) along the main flowpath within the fringe wetland site, as follows:

- Plant community composition data have been summarized (averaged) across each transect for each site. Both total and relative cover of plant taxa were examined. Initial indicators include: relative dominance of invasive species and plant species richness.
- Aquatic macroinvertebrate data were derived from composite samples (3 to 10 D-net sweeps) collected within inundated microsites along the flowpath transects. Initial indicators include taxa richness, Simpsons diversity (1-D) and potential identification of taxa-groups that co-occur across wetlands.
- Water chemistry samples were collected from the main flowpath within the wetland at 100, 300, and 500 m along the flowpath. These data were compared to available benchmarks from regional freshwater systems.
- Soils data were summarized by transect distance for general analysis. Similar to water chemistry, the distribution of these data were compared to soil/sediment benchmarks, as available.

Data evaluation was focused on variation among sample units, both within and across sites, and whether ecologically reasonable patterns were discernible among variables within an attribute class (i.e. among plant, water chemistry, or macroinvertebrate variables). An effort was made to minimize the number of pairwise correlation (or similar) analyses to avoid a large number of potentially spurious relationships and to build on previous work that outlined some fundamental characteristics of this wetland class (see CH2MHill, 2005, CH2MHill, 2006).

Most data manipulation was performed using Microsoft Access and Excel 2010. Data summaries, graphing and statistical analyses were conducted in R 3.1.1 (R Core Team, 2014) and R-Studio (version 0.98.1062; www.rstudio.com/), using various widely available packages. Distinct water sources to fringe wetlands were considered, *a priori*, potentially important drivers of site-scale effects on biological communities, and was overlaid on ordination plots. In addition, comparisons among attribute types (e.g. invertebrates vs. plants) were transformed to a common scale prior to analysis (i.e. plant data was aggregated to site x distance scales (k=3 per site)).

Data analysis for this project first involved a description of the key site characteristics for each fringe wetland site. The next step involved simple summaries of data from biological response indicators (see Section 4.2) or chemical components of wetland surface water and soils. More advanced multivariate techniques, including Nonmetric Multidimensional Scaling (NMDS) ordination or classification and regression trees (CART, implemented as random forest analysis) can then be used to identify and describe patterns within complex community composition and multi-analyte chemical suite datasets.

4.0 Results and Interpretation

4.1 Site Characteristics

Sites were evaluated by desktop and field reconnaissance, as described in Section 2.2. In 2013, only 9 areas were suitable for sampling based on wetland hydrology and site access. Of the non-suitable areas, 10 were much drier than expected, one area was wetter, and one area could not be accessed. Lower water levels in some fringe wetland areas were due to efforts by state land management agencies to reclaim marsh areas invaded by *Phragmites australis* (common reed), an aggressive and noxious weed. Current management techniques include a multi-year drawdown via reduced inflows, combined with periods of intense grazing after herbicide application to inhibit regrowth. Another fringe wetland area, adjacent to a *Phragmites* control area, had water levels 4 to 6 feet (1.2 to 1.8 m) higher than expected and was deemed too dangerous to sample. Higher water levels were a consequence of restricted outflow through 20 culverts along 5 miles of impounded wetland dikes, such that the outflow to the remaining open culvert was increased by over 100 ft^3/sec (estimated) in 2013. Finally, one area could not be sampled due to lack of permission to cross private lands. In 2015, office reconnaissance was performed over several months and a list of nearly 100 potential fringe wetland sites was generated. A total of 15 sites were deemed suitable for sampling in 2015, with three (3) additional sites in the West Desert as potential reference standard sites. Overall, 28 fringe wetland sites were sampling in 2013 and 2015 for this project.

We sampled fringe wetland sites with five distinct water sources, from two GSL bays and one valley in Utah's West Desert, over two separate years (Table 5).

Table 5. Wetland Site Factors

Water Source	Location	Sampling Year
Groundwater (6)	Bear River Bay (11)	2013 (10)
Impoundment (6)	Farmington Bay (14)	2015 (18)
Interior Wetland (6)	West Desert (3)	
Surface Channel (6)		
UPDES (4)		

Site characteristics are shown in (Table 6). Representative wetland areas for sites ranged from < 15 ha to well over 1000 ha, estimated from 2014 imagery (Utah AGRC; {Link}). All sampled sites were well vegetated, with total cover of emergent vegetation ranging from < 20% in submerged aquatic bed and hemi-marsh systems to over 90%, consistent with a mix of saltgrass meadow and emergent marsh communities. Across sites, the total number of plant species within transects (i.e plant species richness) ranged from 2 to 24 (Table 6). Sites with the lowest richness were primarily aquatic areas within hemi-marsh or monocultures of Phragmites australis. By contrast,

Table 6. Summary of Site Characteristics

Site Name	Monitoring Location ID	Latitude	Longitude	Reference Site ?	Water Source *	Wetland Area	Emergent Veg. cover	Plant Species Richness	Invasive Species	Plant Height	Surface Water (cover)	Water depth
ADCO	5972380	40.866	-112.060	-	IW	160.3	84.8	9	73.9	203	82.0	10.5
Bear R Outlet	5972010	41.477	-112.343	-	Chan	1451.5	90.7	15	59.7	110.5	14.5	10.5
Bear Unit2D	5972250	41.435	-112.304	-	IW	316.3	57.4	15	76.6	177.5	11.8	9.2
Bear Unit 7/8	5971990	41.414	-112.216	-	IW	236.9	96.0	12	21.5	151.5	27.0	15.3
CDSD-01	5972340	40.999	-111.953	-	UPDES	120.9	95.8	4	97.9	380.6	43.3	6.7
CDSD-02	5972070	41.001	-111.955	-	UPDES	21.0	85.6	24	34.1	237.9	53.2	7.2
CDSD02-2	5972350	41.001	-111.955	-	UPDES	21.0	98.8	18	34.2	162.1	82.4	3.6
FarmBay Ditch15	5972080	41.063	-112.102	-	Chan	11.4	93.0	13	22.8	151.5	86.2	4.0
FarmBay East01	5971960	40.965	-111.965	-	Interior	> 41.3	53.0	6	0.1	48.5	16.8	6.1
FarmBay East02	5971970	40.960	-111.961	-	Interior	> 37.4	54.5	6	66.9	104.5	32.7	8.1
FarmBay East03	5971980	40.936	-112.008	-	Interior	> 40.9	0	2	0	24.1	22.7	25.3
FB-SERP	5972360	40.918	-111.935	-	IW	190.3	51.7	13	7.1	110.9	67.3	24.9
Foote E	5971930	39.413	-113.874	Y	GW	37.1	99.0	20	0.7	127.3	21.2	3.3
Foote SE	5971934	39.404	-113.866	Y	GW	17.1	48.8	18	0.3	83.3	90.6	6.3
Foote W	5971932	39.413	-113.890	Y	GW	42.6	81.8	8	0.2	147.0	88.8	6.7
GOGGDR	5972390	40.821	-112.135	-	Chan	86.9	50.3	16	74.0	125.0	9.1	4.5
HCrane East	5972280	41.367	-112.146	-	IW	46.3	95.8	14	65.6	256.1	70.4	6.7
NDSD	5972200	41.082	-112.120	-	UPDES	79.0	87.8	22	51.3	260.0	47.0	25.6
Promontory 01	5972300	41.335	-112.406	Y	GW	14.9	64.4	17	0.7	60.0	22.9	2.6
Promontory 13	5972030	41.627	-112.411	Y	GW	68.9	83.9	9	3.3	56.8	24.2	4.0
PSG 01	5972000	41.592	-112.306	-	Interior	16.3	84.8	15	10.3	131.8	47.3	11.3
PSG 06	5972040	41.605	-112.322	-	Chan	23.0	93.9	14	2.4	119.1	100	9.8
PSG 10	5972100	41.596	-112.293	-	IW	18.8	98.9	12	12.7	117.9	77.4	12.8
TNC Ditch10	5972090	41.043	-112.020	-	GW	24.3	99	19	21.3	193.9	50.0	5.3
TNC KC	5972330	41.030	-112.011	-	Chan	39.3	82.1	19	4.7	245.3	78.3	15.1
TNC KC01	5972020	41.030	-112.008	-	Chan	14.9	84.0	19	8.1	125.8	28.0	6.4
WSpur Mid	5972060	41.400	-112.108	-	Interior	43.1	0	2	0	39.3	100	39.3
WSpur Tail	5972050	41.412	-112.088	-	Interior	43.8	18.7	4	0	27.3	100	12.4
(Units)						ha	%	# spp	% (rel. cover)	cm	%	cm

Notes: * Dominant water sources include: IW (Impounded Wetlands); Chan (Channels of short-order streams and canals), UPDES (Municipal wastewater treatment plants with Utah Pollution Discharge Elimination System permits), GW (Groundwater discharge from springs or seeps), Interior (sites within larger wetland complexes, e.g. Willard Spur and portions of Farmington Bay)/

eight sites had more than 18 species, represented by a range of taxa from aquatic to more xeric habitats.

A notable feature of the fringe wetland class is the variety of aquatic vs. terrestrial features among sites. Aquatic features of fringe wetlands are expected to be the most sensitive to direct, discharge-related impacts (such as pollutant loading), due to the greater contact time between aquatic organisms and ambient waters, relative to organisms inhabiting more terrestrial habitats (e.g. aquatic insects or algae vs. terrestrial insects or mosses). We observed a wide range in inundation among sites, from < 10% cover of surface water within the channelized delta of the Goggin Drain to over 80% within marshes below Ambassador Duck Club and Kay's Creek. Mean water depths ranged from less than 5 cm at Promontory Spring (PROM01) and Goggin Drain to over 20 cm within interior marshes of Willard Spur and Farmington Bay, and below North Davis SD wastewater treatment plant.

As described in earlier sections of this report and in previous work (DWQ, 2016), we sought out wetland areas within the semiarid region of Utah's West Desert with similar ecological characteristics and management goals that could serve as potential reference standard sites for GSL wetland assessment purposes. Collaborative work with Utah Geological Survey (UGS) provided an opportunity to gain field experience with groundwater-fed wetlands in Snake Valley and impounded wetlands within Fish Springs National Wildlife Refuge and Clear Lake Waterfowl Management Area, managed by US Fish and Wildlife Service and Utah Division of Wildlife Resources, respectively (DWQ, 2016). Through these efforts we were able to identify at least three marsh-dominated areas in Snake Valley that may serve as reference standards for GSL fringe wetlands, in addition to two groundwater-fed sites along the western shore of Bear River Bay below the Promontory mountains. These sites have been identified in Table 6**Error! Reference source not found.**.

4.2 Biological Response Indicators

The taxonomic composition of both emergent vegetation and benthic macroinvertebrate communities were examined as key biological responses of fringe wetlands to a wide range of potential stresses. Plant community composition data was analyzed after averaging total across each flowpath transect (k=3 per site) for all observed species (see Figure 3). Macroinvertebrate community data were based on composite collections of D-net sweeps in inundated areas located along flowpath transects (k=3 per site).

4.2.1 Plant Community Composition

A total of 69 plant taxa were observed within vegetation plots, including three additional cover elements (floating aquatic vegetation (*Lemna* sp. and surface algae; [FAV]), submerged aquatic vegetation (*Stuckenia* sp., *Ruppia* sp., *Ceratophyllum* sp., and the macroalga *Chara*; [SAV]), and standing dead vegetation' [Dead]) that were treated the same as separate plant taxa. A few plant taxa were combined. For example, *Typha latifolia* and *Typha domingensis*, and *Salicornia rubra* and *Sarcocornia utahensis,* were composited at the genus level (*Typha* and *Salicornia* spp., respectively) because they could not be reliably distinguished in the field.

Patterns among plant taxa were examined using ordination analyses (see next section). To reduce the deleterious effects of rare taxa on community distance measures, 34 species with relative frequency less than 5% of sample units (< 4 of 84 transects) were removed from the dataset prior to multivariate analyses. Of the remaining taxa (35 species), five (5) taxa were common, observed at more than 50% of all sample transects; 15 taxa were frequent, occurring at >10 to 49% of sample plots; and 13 taxa were infrequent, observed at >5 to 9% of sample plots. Characteristics of plant species are shown in Table 7; results are based on mean cover data across transects.

The five (5) most common taxa were the synthetic group Floating Aquatic Vegetation (FAV), together with *Typha* spp., *Schoenoplectus americanus*, *Phragmites australis* and *Distichlis spicata*, observed at over half of all transects (Table 7). FAV includes true floating aquatic plants (e.g. *Lemna minor*) as well as accumulations of mats of filamentous algae on the water surface of fringe wetlands. FAV was commonly an important surface component of hemi-marsh in association with *Schoenoplectus maritimus*, and (less frequently) overlying submerged aquatic vegetation (SAV) such as *Stuckenia pectinata* or *Ruppia* sp. The common, often co-dominant marsh plants of *Typha* spp., *Schoenoplectus americanus*, and *Phragmites australis*, in aggregate accounted for nearly 45% of fringe wetland area.

With respect to *Phragmites australis*, we suspect that our measurements largely refer to the non-native (and invasive) subspecies rather than the native one, given the high plant density and overall vigor (plant heights over 3 m) of the plants in disturbed environments. Distinguishing the native vs. non-native form in the field is difficult and no attempt was made to separate them. *Phragmites* was observed in nearly 64% of all transects and had mean cover of 38.4% where it occurred and 16.3% of all fringe wetland areas surveyed. The frequency and total cover of *Phragmites* from GSL fringe wetlands is similar to recent reports from lower portions of watersheds adjacent to GSL (Menuz et al., 2014; Menuz et al., 2016) as well as GSL Waterfowl Management Areas (Long, 2014). Another fifteen taxa had relative frequencies greater than 10%, and included plants in the SAV physiognomic class (*Stuckenia*, *Ruppia*, *Myriophyllum*, etc.) as well as the characteristic taxa of Great Salt Lake hemi-marsh systems, *Schoenoplectus maritimus*.

Hydrophytic plants with Obligate (OBL) or Facultative Wetland (FACW) wetland indicator status (U.S. Army Corps of Engineers Wetland Plant List [http://rsgisias.crrel.usace.army.mil/NWPL/]) represented 12 of the 20 most common plant taxa (Table 7). Only two taxa (*Lactuca serriola* and *Chenopodium album*) were indicative of drier conditions (Facultative Upland (FACU)) and may be considered *'xeric weeds*'. Interestingly, 14 of 20 taxa were classified as native to Utah, based on the USDA Plants database (http://plants.usda.gov/java/). However, the 'Introduced' plants observed in these fringe wetlands included the widespread and widely acknowledged weedy species *Phragmites australis*, *Polypogon monspeliensis*, *Rumex crispus*, *Atriplex micrantha* (or *A. heterosperma* [syn.]), *Lactuca serriola*, and *Tamarix chinensis* (or *T. ramosissima* [syn.]).

Table 7. Characteristics of Observed Plant Taxa, ranked by relative frequency

Species Name	Species Code [*]	Rel. Freq. [§] (%)	RF Rank	Mean Cover (%) [¤]	Mean Total Cover [Þ] (%)	Cover Rank	Indicator † Status	Native ‡	Plant [**] Group
Floating Aquatic Vegetation **[1]**	FAV	79.8%	1	25.56	13.59	3	*OBL*	*N*	*AQ*
Typha spp.	Typha	70.8%	2	27.09	12.79	4	*OBL*	*N*	Gr
Schoenoplectus americanus	SCAM	69.0%	3	34.34	15.81	2	*OBL*	*N*	Gr
Phragmites australis	PHAU	63.7%	4	38.39	16.30	1	*FACW*	*I*	Gr
Distichilis spicata	DISP	53.0%	5	17.00	6.00	7	*FAC*	*N*	Gr
Submerged Aquatic Vegetation **[2]**	SAV	42.3%	6	44.27	12.46	5	*OBL*	*N*	AQ
Schoenoplectus maritimus	SCMA	32.7%	7	34.82	7.60	6	*OBL*	*N*	Gr
Polypogon monspeliensis	POMO	30.4%	8	2.20	0.44	17	*FACW*	*I*	Gr
Hordeum jubatum	HOJU	25.6%	9	2.27	0.39	20	*FAC*	*N*	Gr
Salicornia rubra	SARU	20.2%	10	5.93	0.80	11	*OBL*	*N*	F
Epilobium ciliatum	EPCI	19.6%	11	1.00	0.13	30	*FACW*	*N*	F
Suaeda calceoliformis	SUCA	19.6%	12	5.28	0.69	12	*FACW*	*N*	F
Rumex crispus	RUCR	16.7%	13	8.25	0.92	9	*FAC*	*I*	F
Juncus arcticus	JUBA	14.9%	14	25.88	2.57	8	*FAC*	*N*	Cyp
Eleocharis palustris	ELPA	14.3%	15	8.47	0.81	10	*OBL*	*N*	F
Ranunculus cymbalaria	RACY	13.7%	16	1.26	0.11	34	*OBL*	*N*	F
Atriplex micrantha	ATHE	13.7%	17	1.95	0.18	24	*NI*	*I*	F
Lactuca serriola	LASE	12.5%	18	0.66	0.05	42	*FACU*	*I*	F
Chenopodium album	CHAL	11.9%	19	4.69	0.37	21	*FACU*	*N*	F
Tamarix chinensis	TARA	11.3%	20	7.37	0.56	15	*FAC*	*I*	SS
Polygonum spp.	POSP	9.5%	21	0.76	0.05	43	*FACW*	*I*	F
Nasturtium officinale	NAOF	9.5%	22	0.48	0.03	45	*OBL*	*I*	F
Solidago canadensis	SOCA	8.9%	23	3.00	0.18	23	*NI*	*N*	F
Schoenoplectus acutus	SCAC	7.7%	24	7.65	0.39	19	*OBL*	*N*	Gr
Poa palustris	POPA	7.7%	25	13.26	0.68	13	*FAC*	*N*	Gr
Bidens cernua	BICE	7.7%	26	2.14	0.11	35	*OBL*	*N*	F
Dead Vegetation **[3]**	DEAD	7.7%	27	9.00	0.46	16	*NI*	*N*	-
Cardaria draba	CADR	7.1%	28	9.28	0.44	18	*NI*	*I*	F
Senecio triangularis	SETR	6.5%	29	14.77	0.64	14	*FACW*	*N*	F
Bassia scoparia	BASC	6.5%	30	3.26	0.14	28	*FAC*	*I*	F / SS
Polygonum lapathifolium	POLA	5.4%	31	0.29	0.01	52	*FACW*	*N*	F
Lepidium latifolium	LELA	4.8%	32	3.65	0.12	33	*FAC*	*I*	F
Sporobolus airoides	SPAI	4.8%	33	4.63	0.15	26	*FAC*	*N*	Gr
Mentha arvensis	MEAR	4.2%	34	4.87	0.14	29	*FACW*	*N*	F
Bromus tectorum	BRTE	4.2%	35	2.40	0.07	40	*NI*	*I*	Gr
Lepidium perfoliatum	LEPE	4.2%	36	0.28	0.01	58	*FACU*	*I*	F
Phalaris arundinaceae	PHAR	4.2%	37	0.02	0.00	65	*FACW*	*N*	Gr
Polygonum aviculare	POAV	3.6%	38	1.97	0.05	44	*FACW*	*I*	F
Solanum dulcamarum	SODU	3.0%	39	6.12	0.12	32	*FAC*	*I*	F
Spergularia maritima	SPEMAR	3.0%	40	8.05	0.16	25	*OBL*	*I*	F
Trifolium repens	TRRE	2.4%	41	7.75	0.12	31	*FACU*	*I*	F
Convolvulus arvensis	COAR	2.4%	42	0.10	0.00	64	*NI*	*I*	F
Unknown Grass	Grass	2.4%	43	4.82	0.08	39	*NI*	*I*	Gr
Sisymbrium altissimum	SIAL	2.4%	44	0.02	0.00	67	*FACU*	*I*	F
Sarcobatus vermiculatus	SAVE	1.8%	45	6.67	0.08	36	*FAC*	*N*	SS
Senecio hydrophilus	SEHY	1.8%	46	0.60	0.01	59	*OBL*	*N*	F
Arctium minus	ARMI	1.2%	47	3.50	0.03	46	*FACU*	*I*	F
Asclepias incarnata	ASIN	1.2%	48	0.03	0.00	67	*OBL*	*N*	F
Carex nebrascensis	CANE	1.2%	49	7.51	0.06	41	*OBL*	*N*	Cyp
Cicuta maculata	CIMA	1.2%	50	1.30	0.01	51	*OBL*	*N*	F
Cirsium vulgare	CIVU	1.2%	51	0.22	0.00	62	*FACU*	*I*	F
Elaeagnus angustifolia	ELAN	1.2%	52	0.51	0.00	60	*FAC*	*I*	SS
Elymus repens	ELRE	1.2%	53	39.01	0.31	22	*FAC*	*I*	Gr
Muhlenbergia asperfolia	MUAS	1.2%	54	2.00	0.02	49	*FACW*	*N*	Gr
Potentilla anserina	POAN	1.2%	55	10.00	0.08	37	*OBL*	*N*	F
Unk Annual Forb	UNKAnn	1.2%	56	18.30	0.15	27	*FACW*	-	F
Alopecurus arundinaceus	ALAR	1.2%	57	1.97	0.02	50	*FAC*	*I*	Gr
Cirsium foliosum	CIFO	1.2%	58	1.07	0.01	53	*NI*	*N*	F
Thinopyrum intermedium	THIN	1.2%	59	9.75	0.08	38	*NI*	*I*	Gr
Veronica anagallis-aquatica	VERANA	1.2%	60	0.03	0.00	67	*OBL*	*N*	F
Asclepias speciosa	ASSP	0.6%	61	2.00	0.01	56	*FAC*	*N*	F
Berula erecta	BEER	0.6%	62	0.02	0.00	69	*OBL*	*N*	F
Castilleja miniata	CAMI	0.6%	63	6.00	0.02	47	*FACW*	*N*	F
Cirsium arvense	CIAR	0.6%	64	0.40	0.00	63	*FACU*	*I*	F
Dipsacus sylvestris	DISY	0.6%	65	2.00	0.01	56	*FAC*	*I*	F
Grindellia squarosa	GRSQ	0.6%	66	5.00	0.02	48	*NI*	*N*	SS
Lactuca tatarica	LATA	0.6%	67	2.00	0.01	56	*FACU*	*N*	F
Leymus salinum	LESA	0.6%	68	2.02	0.01	54	*NI*	*N*	Gr
Pascopyrum smithii	PASM	0.6%	69	1.00	0.00	61	*FAC*	*N*	Gr

Notes: [1] Accumulation of *Lemna minor* on water surface or cohesive mats of algae floating within water column or covering inundated soils; cover aggregated as one class. [2] Aquatic plant species with submerged foliage (*Stuckenia*, *Ruppia*, *Myriophyllum sibiricum*, *Ceratophyllum demersum*, *Chara* (macroalga), *Saggitaria latifolia*, and *Potamogeton crispus*). [3] Standing dead plant stems measured as if alive. [*] Species codes used in field. [§] Total number of transects possible is 168 (6 transects x 28 sites). [¤] Mean plant cover within plots where the species was observed. [Þ] Mean plan cover across all sample plots. [†] Status of hydrophytic plant species, based on the US Army Corps of Engineers plant list for the Arid West region. [‡] Plant native status derived from Menuz et al. (2014). [**] Preliminary grouping of plant species based on their occurrence (aquatic species) and growth form (forbs and grasses).

The relative cover of invasive species among sites ranged from < 1 % to over 95% (Table 6). Eleven sites had low (< 5%) relative cover of invasive taxa, while eight sites were dominated by invasives (relative cover > 50%). Sites with the greatest cover of invasive species typically had lower species richness than sites with low to moderate cover of invasives (Figure 5). Sites with low relative cover of invasives and high taxa richness were predominantly groundwater-fed marshes in northeastern GSL or within the West Desert reference area, while sites with low invasive cover and low taxa richness were dominated by aquatic (versus emergent) plant taxa. In contrast, sites with high relative cover of invasives were typically dominated by extensive stands of *Phragmites*. While the pattern is subtle, increasing dominance of one (or a few) invasive species, whether due to disturbance or nutrient enhancement, can result in competitive exclusion of others in these highly productive wetlands (Mooney and Cleland, 2001; Bertness et al., 2002; Minchinton and Bertness, 2003). A few other invasive species were locally common (> 5% cover) within specific sites: the GOGGDR site (Goggin Drain delta wetland) had substantial cover of *Tamarix* and *Cardaria* (site averages of 14 and 9% cover, respectively), and BROutlet (outlet of Bear River) included *Polypogon monspeliensis* and *Rumex crispus* (site averages of 7 and 31% cover).

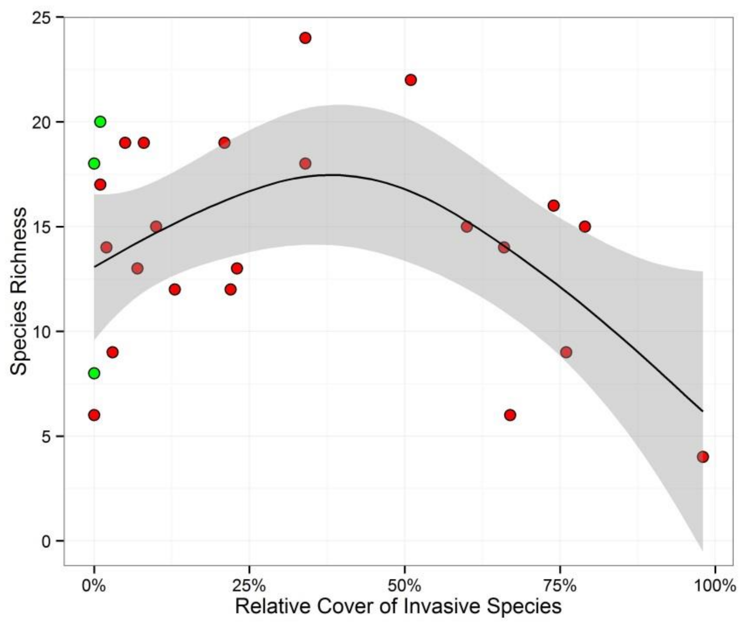

Figure 5. Mean plant species richness vs. relative cover of invasive species, site averages.

Green circles are site mean relative cover of invasive species and species richness for reference standard sites located in Snake Valley, while red circles represent all other fringe wetland sites. Relationship between species richness and relative cover of invasive species was modeled using a generalized additive model, where model df = 1.87, n=25, and 29.4% of deviance explained by model.

4.2.1.1 NMDS Ordination of Plant Community Data

As mentioned above, the full plant community composition dataset was refined prior to NMDS ordination in order to reduce the deleterious effects of rare taxa on community distance measures. As such, 34 plant species with relative frequency < 5% of sample units (fewer than 4 of 84 transects) were removed from the dataset. Ordination was performed using the metaMDS() function in **R** package *vegan* (Oksanen et al., 2016), based on sample (site x transect) dissimilarities calculated by Bray-Curtis distance, after 'Wisconsin-style' double standardization square root transformation. The optimum number of NMDS axes was determined by evaluating the decline in stress after calculating 10 independent metaMDS() runs for 1 to 6 dimensions; the goal was to identify the minimum number of dimensions with stress less than roughly 0.20. Ordination axes were rescaled and rotated such that the first axis (NMDS1) contains the largest proportion of variation among sites in ordination 'species space', i.e. largest differences in plant community composition among sites. Ordination results (NMDS axis scores) were used to try to explain community patterns among sites with respect to distinct water sources and contributing watersheds, the relative importance of individual taxa, and the degree of potential association among site variables, water and soil chemistry, and leaf nutrient concentrations against NMDS axes.

An optimum NMDS solution for plant community composition data contained three axes and a final stress of 0.14. The distribution of plant species and sites (3 transect per site) for all pairs of NMDS axes is shown in Figure 6.

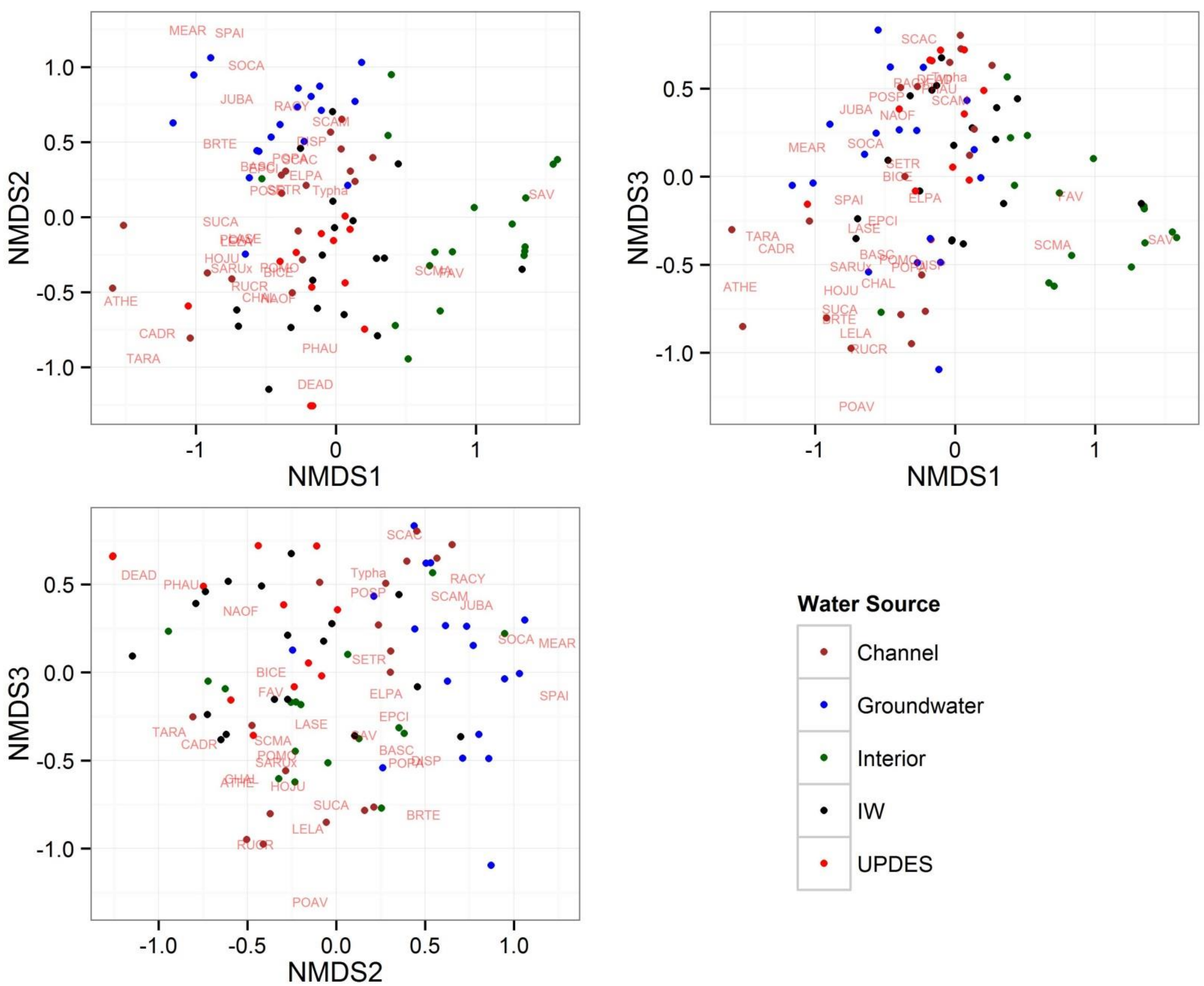

Figure 6. NMDS ordination of plant community data, Sites x Water Source

Plant species codes (red text, see Table 7 for details) illustrate the influence of various plant taxa and site NMDS scores in 'species space'. Solid circles are site x transect samples, shaded by dominant water source.

Plant Taxa

There was modest evidence (p<0.01) for an association between the NMDS axes and 22 of the 35 plant species (Table 8). Axis 1 was appears to describe a gradient of soil moisture availability / water regime, increasing from primarily 'xeric weeds' (e.g. *Atriplex sp.*, *Tamarix*, and *Cardaria*)to more aquatic plant communities (FAV and SAV taxa). Axis 2 spanned a range from high *Phragmites* (low axis 2 values) to taxa representative of rich wet meadow or freshwater marsh communities (e.g., *Mentha*, *Sporobolus*, *Solidago*, and *Schoenoplectus americanus*) (Figure 6). An interpretation for axis 3 was not clear based on plant taxa associations.

Table 8. Associations between plant species and Veg-NMDS axes.

Symbol	Species Name	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit (r^2)	Vector Sig. (P)
PHAU	*Phragmites australis*	-0.14	-0.83	0.55	0.684	0.001
SAV	*Submerged Aquatic Vegetation*	0.92	0.09	-0.39	0.575	0.001
SCAM	*Schoenoplectus americanus*	-0.07	0.78	0.62	0.430	0.001
HOJU	*Hordeum jubatum*	-0.55	-0.24	-0.80	0.301	0.001
FAV	*Floating Aquatic Vegetation*	0.77	-0.56	-0.32	0.301	0.001
Typha	*Typha* spp.	-0.13	0.31	0.94	0.291	0.001
DISP	*Distichlis spicata*	-0.20	0.62	-0.76	0.259	0.001
SARUx	*Salicornia rubra*	-0.49	-0.38	-0.78	0.248	0.001
JUBA	*Juncus balticus*	-0.62	0.73	0.28	0.240	0.001
ATHE	*Atriplex heterosperma* (and syns.)	-0.78	-0.31	-0.55	0.239	0.001
SUCA	*Sueada calceoformis*	-0.57	-0.26	-0.78	0.237	0.001
CHAL	*Chenopodium albidum*	-0.35	-0.47	-0.81	0.228	0.001
POMO	*Polygonum monspeliensis*	-0.34	-0.38	-0.86	0.219	0.001
MEAR	*Mentha arvense*	-0.58	0.80	0.12	0.196	0.001
RUCR	*Rumex crispus*	-0.29	-0.33	-0.90	0.192	0.001
SCMA	*Schoenoplectus maritimus*	0.60	-0.46	-0.66	0.161	0.002
LELA	*Lepidium lotifolium*	-0.33	-0.17	-0.93	0.159	0.002
SOCA	*Solidago Canadensis*	-0.53	0.84	0.13	0.159	0.001
SPAI	*Sporobolus airoides*	-0.58	0.81	-0.04	0.149	0.002
POAV	*Polygonum aviculare*	-0.32	-0.09	-0.94	0.141	0.006
CADR	*Cardaria draba*	-0.81	-0.47	-0.36	0.110	0.009
TARA	*Tamarix ramosissima*	-0.83	-0.46	-0.32	0.104	0.003

Strength of association based on Pearson's (r) statistic, for variables with vector significant at p ≤ 0.01.

Environmental Site Factors

Sample sites groups by watersheds or dominant water source had distinct patterns of plant community composition, based on permutation tests on NMDS scores (p < 0.001; centroids of factor levels). Figure 7 illustrates differences in plant community composition among water sources sources, where shaded polygons represent convex hulls around all points for a given water source. Samples characterized by mainly aquatic habitats were most common in fringe wetlands located within larger wetland complexes (*vis.* wetland 'Interiors', such as hemi-marsh portions of Farmington Bay and Willard Spur), as well as sites receiving water from shallow impounded wetlands (middle right portion of Figure 7). Drier habitats were most common in areas with channelized flowpaths (lower left). Transects dominated by *Phragmites australis* were found in wetlands receiving water from impounded wetlands or UPDES-effluent discharges, and were intermediate along an apparent moisture gradient (upper center of figure).

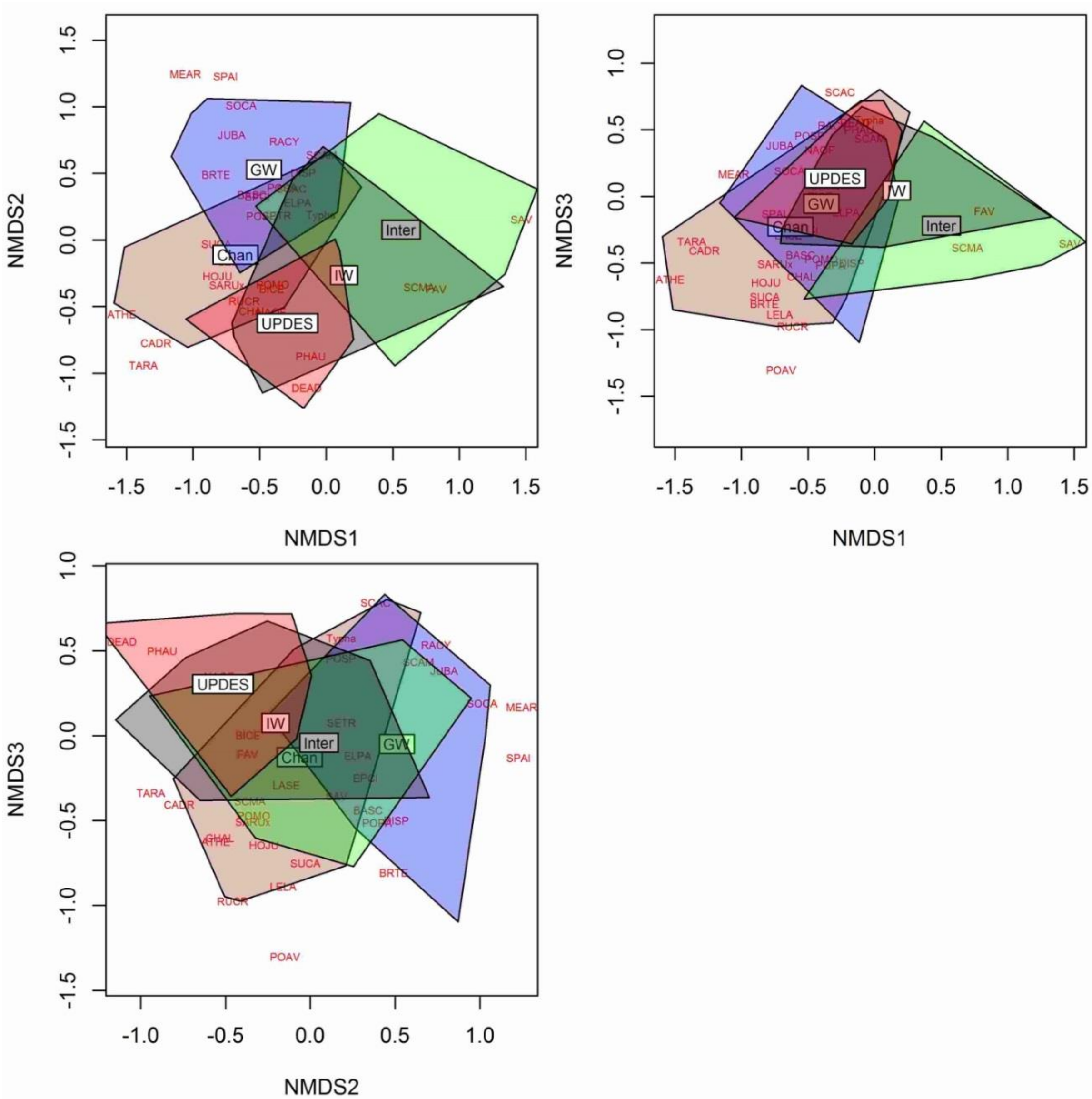

Figure 7. NMDS ordination of plant community data, Species x Water Source

Plant species codes (see Table 7) and convex hulls (shaded polygons) around dominant water sources for fringe wetland sites. Water sources coded as follows: GW = groundwater (blue); Inter = interior wetlands (green); IW = impounded wetlands (gray); UPDES = treated wastewater discharge (red); Chan = stream and canal channels (tan).

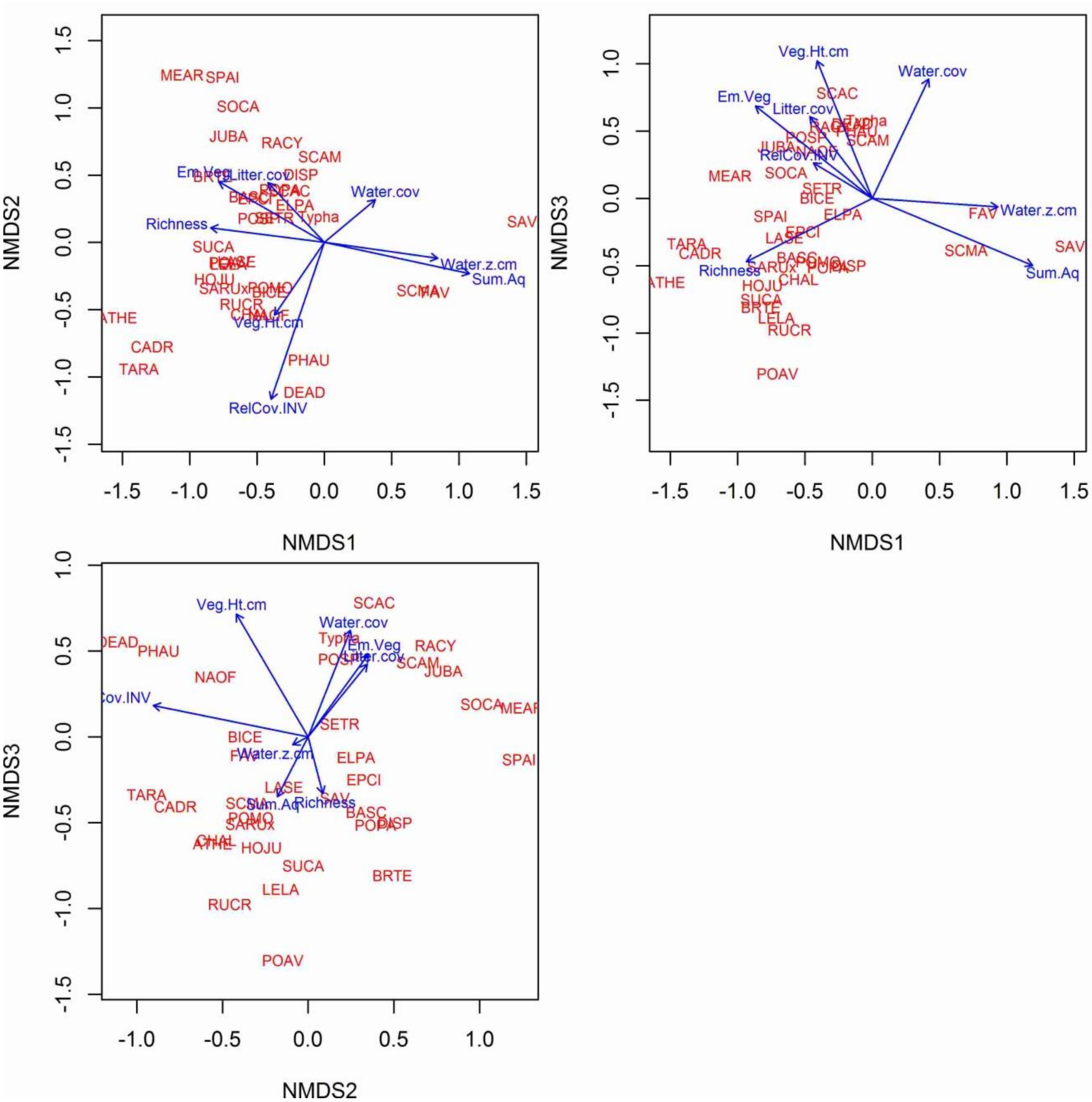

Figure 8. Plant community NMDS ordination and significant environmental site variables.

Ordination plot showing plant taxa (red text) and vectors (blue rays) having significant association with site variables.

Environmental Site Variables

There was strong evidence ($p<0.005$) for an association between all 9 environmental site variables and plant community NMDS axes (Table 9). Positive values along NMDS axis 1 were associated with aquatic features of fringe wetlands, while negative values increased with total cover of both emergent vegetation and surface litter and plant species richness (Figure 8). Negative values along NMDS axis 2 were associated with relative cover of invasive species (dominated by *Phragmites*) and plant height.

Interestingly, litter cover is not well aligned with the cover of *Phragmites* or standing dead vegetation (taxa code: DEAD), even though dense *Phragmites* stands are widely acknowledged to contain formidable accumulations of raised litter. It may be that *Phragmites*-dominated areas examined during this two-year survey (2013 and 2015) were relatively recently invaded, such that large accumulations of litter had not yet developed.

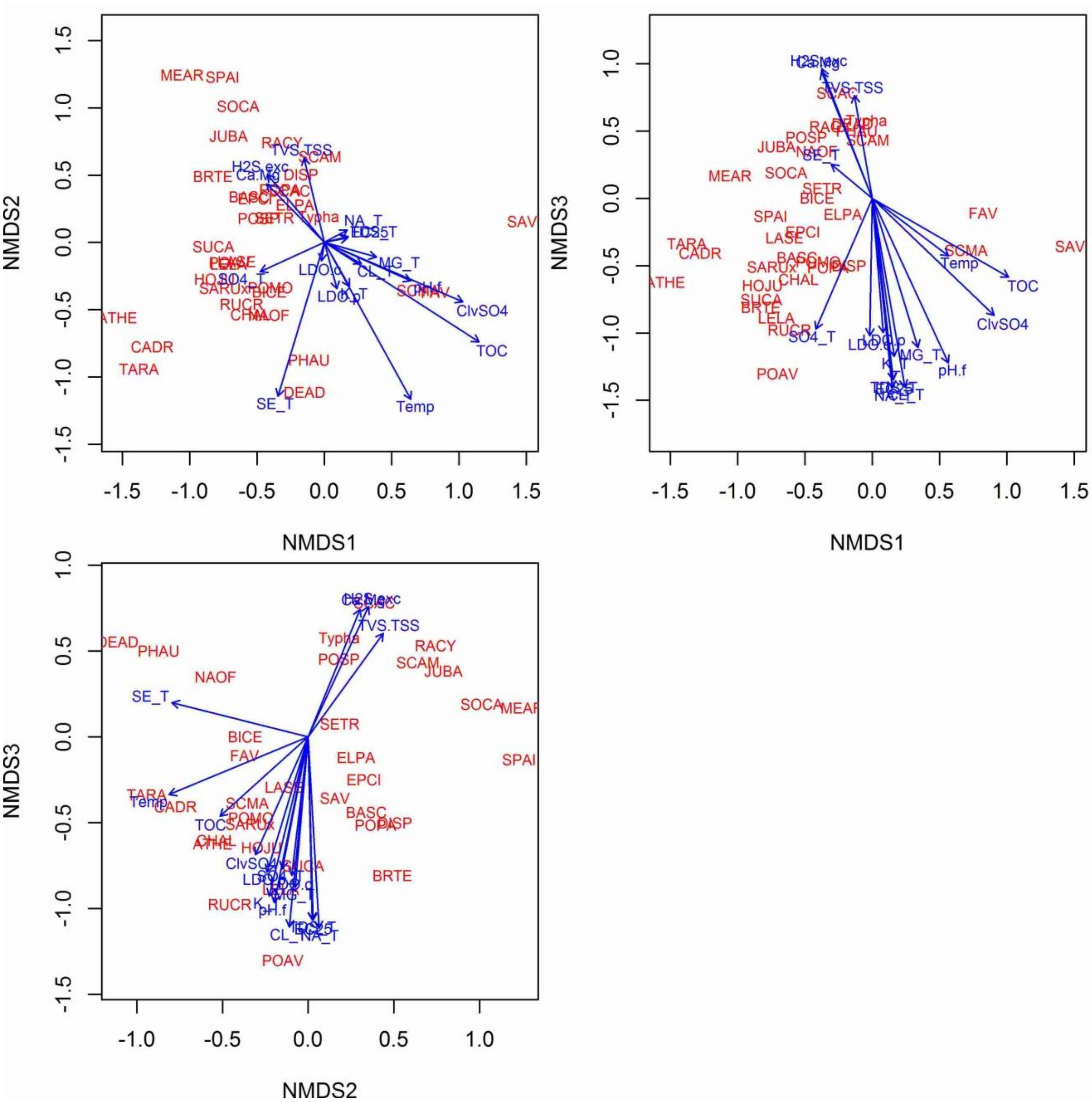

Figure 9. Plant community NMDS ordination and water chemistry variables

Ordination plot showing plant taxa (red text) and vectors (blue rays) having significant association with water chemistry variables.

Water Chemistry

There was modest evidence ($p<0.005$) for an association between 17 of 46 water chemistry variables and plant community NMDS axes (Table 9). While many water chemistry variables appear to be correlated (Figure 9), the five water chemistry variables with the highest vector r^2 values were strongly (*negatively*) associated with NMDS axis 3, and largely represented elements of water salinity. Axis 1 appeared to be only modestly associated with water chemistry variables, largely with increasing TOC concentrations and Cl:SO_4 ratios along the positive axis (presumably higher in more open aquatic and hemi-marsh areas of interior waters), while axis 2 increased with increasing TVS:TSS ratio (proportion of suspended solids as organic matter) and decreased with increasing water temperatures. Broadly, the third axis describing plant community composition appears to be related to salinity.

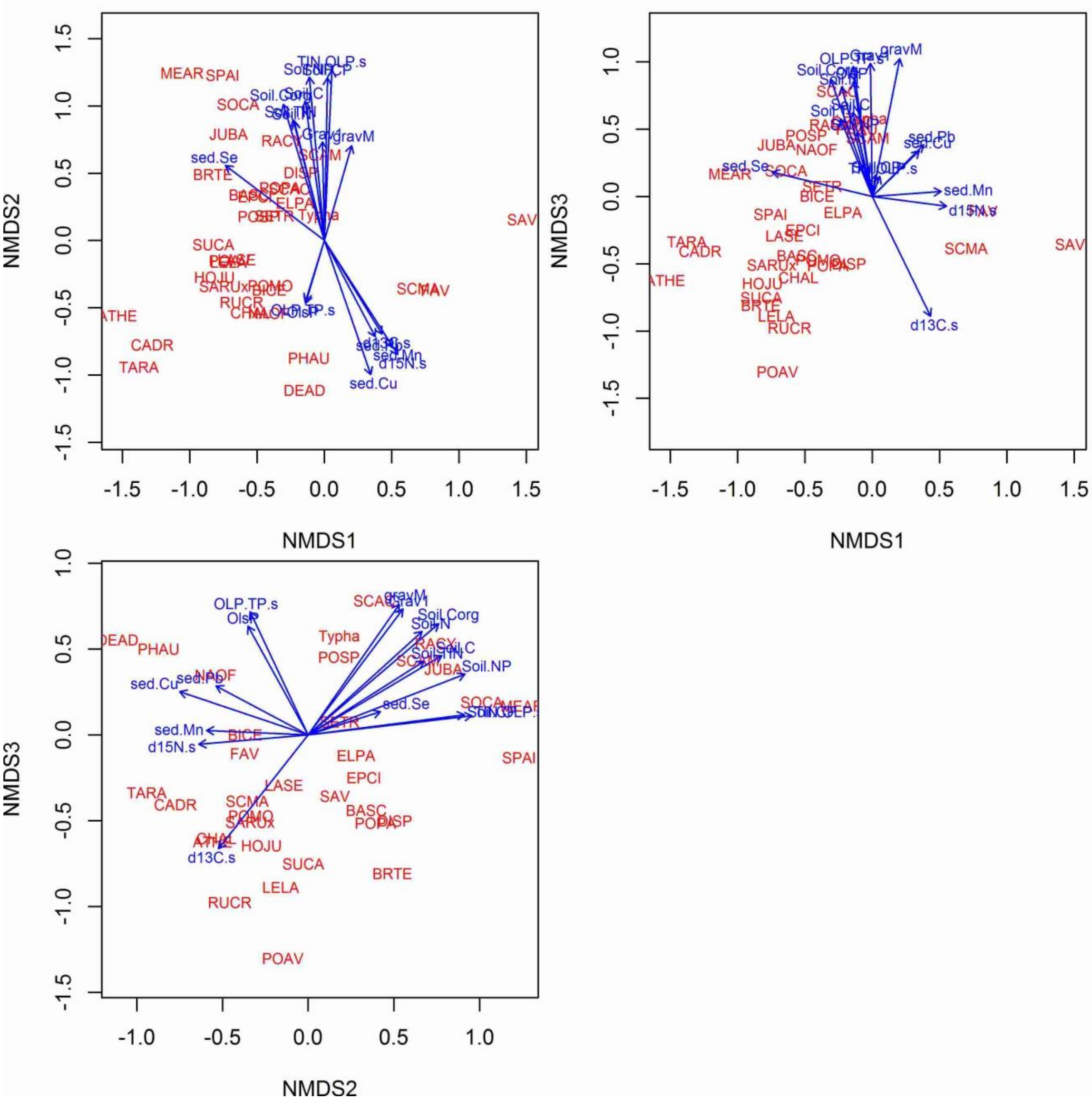

Figure 10. Plant community NMDS ordination and significant soil chemistry variables.

Ordination plot showing plant taxa (red text) and vectors (blue rays) having significant association with soil chemistry variables.

Soil Chemistry

There was modest evidence ($p<0.01$) for an association between 18 of 29 soil chemistry variables and plant community NMDS axes (Table 9). Similar to water chemistry, many soil chemistry variables appear to be highly correlated among the fringe wetland sites surveyed here (Figure 10). Few soil chemistry variables were strongly associated with axis 1. Instead, most variables were strongly associated with axis 2.

Since NMDS axes were rotated to maximize variation in plant community composition along Axis 1, the above result suggests that a large fraction of variation in plant community composition *was not* driven by variables describing soil chemistry. Two clusters of strong ($p<0.002$) associations were observed along axis 2 (Figure 10). One cluster includes soil concentrations of Copper, Lead and Manganese, and natural abundance stable isotope

Table 9. Associations between Environmental Variables and Veg-NMDS axes.

Variable Code	Site Variable	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector (r^2)	(P)
Site Variables						
RelCov.INV	*Rel. Cover of Invasive Plant Taxa*	-0.32	-0.93	0.19	0.767	0.001
Sum.Aq	*Total Cover of Aquatic Plant Taxa*	0.91	-0.19	-0.38	0.692	0.001
Veg.Ht.cm	*Dominant Vegetation Height (cm)*	-0.33	-0.48	0.82	0.626	0.001
Em.Veg	*Total Cover of Emergent Plant Taxa*	-0.72	0.41	0.56	0.589	0.001
Richness	*Total Plant Taxa Richness*	-0.89	0.11	-0.45	0.443	0.001
Water.cov	*Total Cover of Water*	0.40	0.34	0.85	0.432	0.001
Water.z.cm	*Water Depth (cm)*	0.99	-0.14	-0.07	0.355	0.001
Litter.cov	*Total Cover of Surface Litter*	-0.51	0.54	0.67	0.328	0.001
Bare.mud	*Total Cover of (moist) Bare Soil*	-0.59	-0.50	-0.63	0.143	0.005
Water Chemistry						
CL_T	*Total Chloride (mg/L)*	0.17	-0.10	-0.98	0.362	0.001
NA_T	*Total Sodium (mg/L)*	0.11	0.06	-0.99	0.358	0.001
pH.f	*Water pH (field probe)*	0.41	-0.18	-0.89	0.332	0.001
EC25	*Specific Conductivity (25C; field)*	0.11	0.03	-0.99	0.328	0.001
TDS_T	*Total Dissolved Solutes (mg/L)*	0.11	0.02	-0.99	0.327	0.001
TOC	*Total Organic Carbon (mg/L)*	0.76	-0.49	-0.44	0.317	0.001
ClvSO4	*Chloride to Sulfate ratio (mass ratio)*	0.69	-0.30	-0.66	0.306	0.001
Temp	*Water Temperature (field probe)*	0.45	-0.82	-0.34	0.276	0.001
K_T	*Total Potassium (mg/L)*	0.13	-0.24	-0.96	0.263	0.001
MG_T	*Total Magnesium (mg/L)*	0.29	-0.08	-0.95	0.239	0.001
H2S.exc	*Exceedance of H_2S criterion (binary)*	-0.33	0.40	0.86	0.224	0.002
Ca.Mg	*Calcium to Magnesium ratio (mass)*	-0.35	0.35	0.87	0.208	0.001
SE_T	*Total Selenium (µg/L)*	-0.28	-0.93	0.23	0.207	0.002
SO4_T	*Total Sulfate (mg/L)*	-0.39	-0.18	-0.90	0.205	0.002
LDO.p	*Dissolved O_2 (% of saturation)*	0.08	-0.29	-0.95	0.194	0.001
LDO.c	*Dissolved O_2 (mg O_2/L)*	-0.02	-0.12	-0.99	0.187	0.003
TVS.TSS	*Organic fraction of Suspended Solids*	-0.14	0.58	0.80	0.160	0.004
Soil Chemistry						
Soil.Corg	*Soil Organic Carbon (g/kg)*	-0.22	0.74	0.63	0.419	0.001
Soil.NP	*Soil Nitrogen to Phosphorus ratio*	-0.08	0.93	0.36	0.386	0.001
TIN.OLP.s	*TIN to Olsen-P ratio*	0.04	0.99	0.12	0.369	0.001
grav1	*Soil Moisture (g/g)*	0.16	0.56	0.81	0.352	0.001
Soil.CP	*Soil Total Carbon to Phosphorus ratio*	0.02	0.99	0.13	0.336	0.001
Soil.C	*Soil Total Carbon (g/kg)*	-0.12	0.85	0.51	0.332	0.001
Soil.N	*Soil Nitrogen (g/kg)*	-0.19	0.73	0.66	0.331	0.001
d13C.s	*Soil Total C isotope signature ($\delta^{13}C$)*	0.36	-0.58	-0.73	0.325	0.001
sed.Cu	*Soil Copper (mg/kg)*	0.31	-0.90	0.30	0.276	0.001
Soil.TIN	*Soil Total Inorganic Nitrogen (mg/kg)*	-0.21	0.82	0.52	0.267	0.001
OLP.TP.s	*Soil Olsen-P to Total P ratio (mass)*	-0.13	-0.42	0.90	0.256	0.001
OlsP	*Soil Olsen-P (mg/kg)*	-0.14	-0.48	0.87	0.214	0.001
sed.Se	*Soil Selenium (mg/kg)*	-0.78	0.59	0.19	0.200	0.001
d15N.s	*Soil N isotope signature ($\delta^{15}N$)*	0.54	-0.84	-0.07	0.230	0.002
sed.Mn	*Soil Manganese (mg/kg)*	0.54	-0.84	0.04	0.198	0.002
sed.Pb	*Soil Lead (mg/kg)*	0.42	-0.80	0.42	0.179	0.002
Soil.P	*Soil Total Phosphorus (g/kg)*	-0.53	-0.62	0.57	0.135	0.007
Soil.CN	*Soil Carbon to Nitrogen ratio (mass)*	-0.19	-0.57	-0.80	0.143	0.008
Leaf Nutrient Concentrations						
Veg.CN	*Leaf Carbon to Nitrogen ratio (mass)*	-0.48	0.84	0.26	0.464	0.001
d13C	*Leaf Carbon isotope signature ($\delta^{13}C$)*	0.67	0.16	-0.72	0.402	0.001
Veg.N	*Leaf Nitrogen (mg/g)*	0.28	-0.96	-0.04	0.398	0.001
Veg.CP	*Leaf Carbon to Phosphorus ratio*	-0.19	0.98	-0.03	0.363	0.001
d15N	*Leaf Nitrogen isotope signature ($\delta^{15}N$)*	0.01	-0.98	0.21	0.359	0.001
Veg.C	*Leaf Carbon (mg/g)*	-0.46	-0.40	0.79	0.284	0.001
Veg.P	*Leaf Phosphorus (mg/g)*	-0.04	-0.61	0.79	0.180	0.002
Veg.NP	*Leaf Nitrogen to Phosphorus ratio*	0.04	0.94	-0.35	0.166	0.002

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \le 0.005$.

ratios of soil (total) Carbon and Nitrogen ($\delta^{13}C$ and $\delta^{15}N$, respectively); these increased along negative axis 2 values. An association between soil Cu, Pb and Mn concentrations and stable isotopes is not readily apparent, however, higher $\delta^{13}C$ values are likely indicative of greater soil inorganic C content (as carbonates), which may allow sorption of relatively labile Cu and Mn species at higher pH (Alloway, 2013).

The second cluster was predominantly nutrient-related variables that increased with along positive axis 2 values, including soil organic carbon concentrations and available nutrient ratios (N to P and TIN to Olsen-P ratios). This cluster appears to be associated higher soil organic matter content in *Schoenoplectus* marsh communities receiving groundwater as a dominant water source, as observed at FooteWest, FooteSe and PSG01 sites. Based on adjacent land use of the contributing area and groundwater sources to these wetland sites, *Schoenoplectus* marsh may be an important characteristic of fringe wetland 'reference standards' that accumulate soil organic C and may have P-limitations to plant growth, as evidences by higher TIN to Olsen-P ratios.

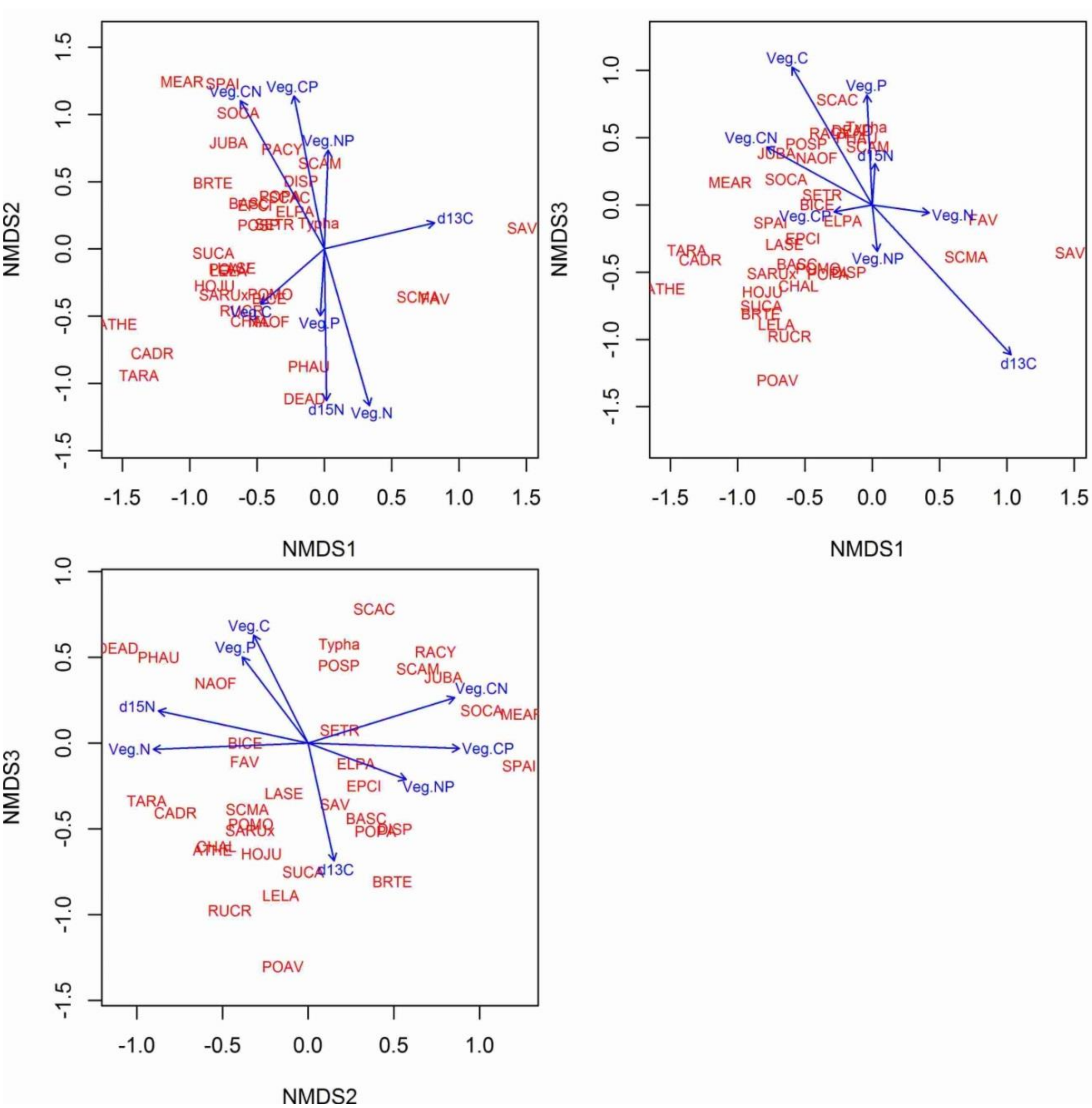

Figure 11. Plant community NMDS ordination and significant leaf chemistry variables

Ordination plot showing plant taxa (red text) and vectors (blue rays) having significant association with leaf nutrient chemistry variables.

Leaf Nutrients

There was strong evidence ($p \leq 0.002$) for an association between all 8 (leaf) chemistry variables and plant community NMDS axes (Table 9). Once again, environmental (leaf chemistry) variables were not strongly correlated with the first (major) plant community axis (Figure 11), except that leaf $\delta^{13}C$ values increased in SAV-dominated sites, mainly as a consequence of reliance of dissolved versus gaseous forms of CO_2 during photosynthetic C fixation (Farquhar et al., 1989; Keeley and Sandquist, 1992; Cloern et al., 2002). Axis 2 values were negatively associated with leaf $\delta^{15}N$ stable isotope signatures and leaf N concentrations, and negatively associated with leaf Carbon to Nitrogen (C:N), Carbon to Phosphorus (C:P), and Nitrogen to Phosphorus (N:P) ratios. Based on the above result, there appears to be a strong N-driven gradient in nutrient availability, with *Phragmites*-dominated stands downstream of wastewater treatment plants or within Farmington Bay having relatively high N (and/or P) availability, while *Schoenoplectus*-dominated stands fed by groundwater sources have wide (high) soil TIN:Olsen-P ratios and leaf N:P ratios.

4.2.2 Wetland Macroinvertebrates

A total of 67 aquatic and two terrestrial macroinvertebrate taxa were identified from samples collected at 83 locations within 28 fringe wetland sites (Table 10). Invertebrate abundance data were aggregated by taxon names provided by Dr. Larry Gray (Utah Valley University). The relative abundance of 40 taxa were analyzed for patterns in community composition after removal of taxa occurring at less than four sites (lower than 5% relative frequency). Six taxa were widespread, observed in at least 40% of wetland sites sampled in 2013 and 2015: three subfamilies of chironomids (non-biting midges), an amphipod (*Hyalella azteca*), a mayfly (*Callibaetis*), and a water boatman (*Corisella*). These taxa were also quite abundant where they occurred. The most abundant taxa were chironomids of genus *Chironomus* and sub-family Tanypodinae, with average abundance of 250 and 109 individuals / m^2 (where they occurred), respectively. Other occasionally abundant taxa were the snails *Potamopyrgus* (162 / m^2; 2 sites), *Pyrgulopsis* (130 / m^2; 3 sites), and *Stagnicola* (72 / m^2; 17 sites).

Across sites, the number of distinct taxa (taxa richness) ranged from 2 to 23. For transects, taxa richness ranged from 1 (eight transects) to 16 (two transects) (Table 11). It is possible that estimates of macroinvertebrate community diversity were underestimated due to low invertebrate abundance in some samples (Table 11). As a general rule, more than 200 individuals are preferred for an appropriate evaluation of community composition (King and Richardson, 2002). Of the 83 macroinvertebrate samples collected, 44 samples had fewer than 200 individuals, and the geometric mean abundance of invertebrates across all samples was 157 (median = 147).

There was little evidence for a systematic increase in invertebrate taxa richness for samples with 50 to 150 individuals per sample compared to those with over 200 individuals per sample. However, future work should more closely investigate the relationship between invertebrate abundance and richness (and other diversity measures; *sensu* Gotelli and Colwell, 2001) across the gradient of fringe wetland communities.

Table 10. Macroinvertebrate Taxa Collected.

Major Group:	Family	Lowest taxonomic Unit	Taxon Code	Feeding [1] Group	Rel. Freq. samples [2]	Rel. Freq. sites
Ephemeroptera	Baetidae	*Callibaetis*	Calli	GC	41%	57%
	Caenidae	Caenis	Caeni	GC	10%	18%
	Leptohyphidae	Tricorythodes	Trico	GC	6%	7%
:Trichoptera	Hydropsychidae	Cheumatopsyche	Cheum	CG	5%	7%
	Phryganeidae	*Phryganea*	Phryg	SH	10%	25%
	Hydroptilidae	*Ochrotrichia*	none	PH	2%	7%
:Odonata	Aeshnidae	*Aeshna*	Aeshn	PR	18%	39%
	Corduliidae	*Somatochlora*	Somat	PR	7%	11%
	Gomphidae	*Ophiogomphus*	353	PR	4%	4%
	Libellulidae	*Erythemis*	Eryth	PR	6%	14%
	Libellulidae	*Libellula*	356	PR	2%	4%
	Libellulidae	*Sympetrum*	Symp	PR	6%	7%
	Calopterygidae	*Hetaerina*	348	PR	4%	11%
	Coenagrionidae	*Enallagma*	Enall	PR	20%	32%
	Coenagrionidae	*Ischnura*	Isch	PR	25%	36%
:Hemiptera	Belostomatidae	*Lethocerus*	329	PR	1%	4%
	Corixidae	*Corisella*	Coris	PR	41%	50%
	Corixidae	*Hesperocorixa*	Hesper	PR / PH	14%	21%
	Corixidae	*Sigara*	330	PR	2%	4%
	Naucoridae	*Ambrysus*	333	PR	1%	4%
	Notonectidae	*Notonecta*	Noton	PR	33%	43%
:Diptera	Dolichopodidae	sp.	226	PR	2%	7%
	Ephydridae	*Ephydra*	Ephy	GC	7%	14%
	Ephydridae	*Notiphila*	Notip	GC	6%	11%
	Sciomyzidae	*Sepedon*	243	PR	2%	7%
	Stratiomyidae	*Caloparyphus*	Calop	GC	6%	18%
	Syrphidae	*Eristalis*	521	GC	4%	7%
	Tabanidae	*Chrysops*	Chrys	PR	11%	18%
	Tabanidae	*Tabanus*	249	PR	1%	4%
	Ceratopogonidae	subfam. Ceratopogoninae	Cerato	PR	5%	11%
	Chironomidae	*Chironomus*	Chiron	GC	45%	57%
	Chironomidae	tribe Tanytarsini	Tanyt	GC	28%	50%
	Chironomidae	sp.	Chir.x	GC	20%	29%
	Chironomidae	subfamily Orthocladiinae	Orthoc	GC	41%	64%
	Chironomidae	subfamily Tanypodinae	Tanyp	PR	60%	79%
	Culicidae	sp.	221	GC	4%	11%
	Tipulidae	*Holorusia*	hol	SH	1%	4%
	Tipulidae	*sp.*	250	CG	1%	4%
:Coleoptera	Chrysomelidae	*sp.*	none	SH	4%	7%
	Dytiscidae	*Agabus*	16	PR	1%	4%
	Dytiscidae	*Hydroporus*	Hydop	PR	6%	11%
	Dytiscidae	*Laccophilus*	Lacco	PR	11%	21%
	Dytiscidae	*Stictotarsus*	Stict	PR	12%	18%
	Dytiscidae	*sp.*	46	PR	1%	4%
	Hydrophilidae	*Berosus*	Beros	CG	13%	21%
	Hydrophilidae	*Enochrus*	Enoch	CG	34%	54%
	Hydrophilidae	*Hydrophilus*	69	PR	1%	4%
	Hydrophilidae	*Tropisternus*	Trop	PR / CG	10%	21%
	Gyrinidae	*Gyrinus*	50	PR	1%	4%
	Scirtidae	*Cyphon*	cyp	SC	2%	7%
Crustacea: Amphipoda	Gammaridae	*Gammarus*	Gamm	CG	5%	7%
	Hyalellidae	*Hyalella azteca*	Hyal	GC	45%	57%
:Decapoda	Astacidae	*Pacifastacus*	490	OM	2%	4%
:Isopoda	Asellidae	*Caecidotea*	Caec	GC	10%	18%
Mollusca: Bivalvia	Sphaeriidae	sp.	499	FC	2%	7%
	Unionidae	*Anodonta*	497	FC	1%	4%
:Gastropoda	Physidae	*Stagnicola*	Stagn	SC	20%	29%
	Physidae	*Physa*	Physa	SC	33%	50%
	Physidae	*Physella*	Physel	SC	16%	25%
	Planorbidae	*Gyraulus*	Gyr	SC	6%	14%
	Hydrobiidae	*Potamopyrgus*	507	SC	2%	4%
	Hydrobiidae	*Pyrgulopsis*	508	SC	4%	4%
	Succineidae	*Oxyloma*	oxy	SC	2%	4%
Annelida: Hirundinea	Erpobdellidae	sp.	Erpob	PR	6%	14%
	Glossiphoniidae	*Helobdella*	Helob	PR	6%	14%
:Oligochaeta	Naididae	sp.	Naid	GC	13%	29%
Platyhelminthes (Turbellaria)		sp.	513	PR	1%	4%

Notes: Taxonomic data provided by Dr. Larry Gray (Utah Valley University). [1] Feeding groups: GC = gatherer-collector, OM = omnivore, PH = piercer-herbivore, PR = predator, SC = scraper, SH = shredder. [2] Proportion of sites where taxa was collected (83 samples were collected); taxa with relative frequency <5% were aggregated by Taxon Code or omitted from further analysis. (n/a) Terrestrial invertebrates were not included in analysis.

Table 11. Site Summary for Benthic Macroinvertebrate Community Data.

Site	Distance [1]	Total Count [2]	Rank of Counts	Taxa [3] Richness	Rank of Richness	Site Richness	Evenness [4]	Shannon's Diversity (H') [5]	Simpson's Diversity [6]
Foote East	100	16	74	7	49.5	18	0.92	1.79	0.81
	300	58	57	13	10		0.80	2.06	0.83
	500	29	66.5	7	49.5		0.76	1.48	0.71
Foote West	100	34	64	4	63.5	9	0.75	1.04	0.60
	300	7	77	5	58		0.96	1.55	0.78
	500	28	68.5	8	41.5		0.77	1.60	0.73
Foote SE	100	24	71.5	8	41.5	18	0.88	1.83	0.82
	300	99	48	14	7		0.79	2.08	0.81
	500	77	53	11	19		0.75	1.80	0.78
FB East 01	100	337	32	10	26.5	13	0.61	1.40	0.68
	300	420	26	11	19		0.68	1.62	0.72
	500	336	33	10	26.5		0.76	1.76	0.78
FB East 02	100	13831	1	7	49.5	11	0.15	0.29	0.15
	300	1421	10	8	41.5		0.42	0.87	0.43
	500	2728	7	11	19		0.57	1.37	0.67
FB East 03	100	1163	14	9	34	13	0.69	1.52	0.72
	300	827	20	11	19		0.73	1.76	0.77
	500	1047	16	11	19		0.56	1.35	0.62
WSpur Tail	100	987	18	12	13.5	15	0.63	1.55	0.68
	300	108	46	14	7		0.77	2.03	0.81
	500	86	50	10	26.5		0.73	1.68	0.75
WSpur Mid	100	183	40	16	3	18	0.70	1.95	0.79
	300	147	42	13	10		0.76	1.95	0.82
	500	662	23	7	49.5		0.75	1.45	0.73
TNC KC2	100	215	39	7	49.5	11	0.32	0.62	0.27
	300	413	27	5	58		0.42	0.75	0.45
	500	1104	15	9	34		0.54	1.24	0.66
PROM 13	100	1235	12	7	49.5	10	0.14	0.26	0.10
	300	4300	6	7	49.5		0.70	1.35	0.71
	500	1502	8	8	41.5		0.69	1.43	0.68
PROM_01	100	1363	11	5	58	9	0.06	0.09	0.03
	300	76	54	5	58		0.43	0.70	0.38
	500	822	21	2	72.5		0.02	0.02	0.00
PSG 01	100	32	65	10	26.5	14	0.87	2.01	0.84
	300	41	61	8	41.5		0.76	1.57	0.73
	500	103	47	10	26.5		0.64	1.47	0.67
PSG 06	100	80	52	11	19	15	0.79	1.90	0.80
	300	374	29	7	49.5		0.44	0.85	0.42
	500	267	36	12	13.5		0.65	1.61	0.73
PSG 10	100	25	70	9	34	11	0.71	1.56	0.68
	300	353	31	6	54.5		0.22	0.39	0.16
	500	19	73	4	63.5		0.76	1.06	0.55
FB Ditch 15	100	1	82.5	1	80.5	10	*NA*	0.00	0.00
	300	6	78	2	72.5		0.65	0.45	0.28
	500	236	38	9	34		0.78	1.72	0.78
TNC Ditch 10	100	40	62.5	12	13.5	17	0.83	2.06	0.82
	300	91	49	10	26.5		0.59	1.36	0.60
	500	140	43	10	26.5		0.35	0.80	0.31
BRMBR-U2D	100	83	51	2	72.5	2	0.95	0.66	0.47
	300	1	82.5	1	80.5		*NA*	0.00	0.00
	500	3	81	2	72.5		0.92	0.64	0.44

Site	Distance [1]	Total Count [2]	Rank of Counts	Taxa [3] Richness	Rank of Richness	Site Richness	Evenness [4]	Shannon's Diversity (H') [5]	Simpson's Diversity [6]
BRU 78	100	373	30	9	34	14	0.43	0.96	0.51
	300	254	37	10	26.5		0.46	1.05	0.49
	500	1039	17	8	41.5		0.67	1.39	0.67
BR Outlet	100	112	44.5	4	63.5	15	0.11	0.15	0.05
	300	333	34	14	7		0.65	1.71	0.74
	500	112	44.5	12	13.5		0.79	1.96	0.81
GOGG	100	28	68.5	4	63.5	4	0.63	0.88	0.50
	300	63	55	1	80.5		*NA*	0.00	0.00
	500	58	57	1	80.5		*NA*	0.00	0.00
TNCKC	100	621	24	6	54.5	14	0.73	1.30	0.67
	300	154	41	8	41.5		0.50	1.04	0.52
	500	44	60	9	34		0.60	1.32	0.55
NDSD	100	10800	2	1	80.5	2	*NA*	0.00	0.00
	300	1500	9	2	72.5		0.10	0.07	0.03
	500	8200	4	2	72.5		0.10	0.07	0.02
CDSD	100					6			
	300	24	71.5	3	67		0.42	0.46	0.23
	500	29	66.5	4	63.5		0.74	1.02	0.59
CDSD02	100	5	79	2	72.5	19	0.97	0.67	0.48
	300	788	22	16	3		0.15	0.41	0.13
	500	297	35	9	34		0.42	0.93	0.44
CDSD02-2	100	460	25	1	80.5	6	*NA*	0.00	0.00
	300	8	76	2	72.5		0.81	0.56	0.38
	500	58	57	4	63.5		0.30	0.42	0.19
HCND	100	40	62.5	5	58	23	0.77	1.24	0.64
	300	912	19	19	1		0.48	1.41	0.55
	500	1204	13	15	5		0.67	1.81	0.75
FB-SERP	100	4	80	2	72.5	12	0.81	0.56	0.38
	300	46	59	11	19		0.77	1.86	0.79
	500	10	75	2	72.5		1.00	0.69	0.50
ADCO	100	6733	5	16	3	23	0.49	1.37	0.67
	300	391	28	8	41.5		0.37	0.77	0.38
	500	8649	3	13	10		0.23	0.60	0.35

Notes: [1] Distance from inflow, along main flowpath, in meters. [2] Total number of individuals observed from a composite sample of 5 to 10 sweeps. A minimum count of > 200 individuals is preferred for evaluation of community composition: 44 of 83 samples had insufficient observations. [3] Number of distinct taxonomic units observed within sample; the lowest level of identifiable resolution may differ among taxonomic groups. [4] Evenness calculated as H' / ln(*Richness*). [5] Shannon's Diversity Index (H') calculated as $-\sum p_i/\ln(p_i)$. [6] Simpson's Diversity Index calculated as $1-\sum(p_i)^2$; p_i is relative abundance of element *i*.

4.2.2.1 NMDS Ordination of Macroinvertebrate Community Data

An optimum NMDS solution for macroinvertebrate community composition was obtained from macroinvertebrate sample abundance data from all sites for taxa with relative frequency > 5%, using the **R** package *vegan* (Oksanen et al., 2016). The ordination was calculated on dissimilarities the same way as described for plant community composition (above). Ordination results were examined in light of distinct water sources and contributing watersheds among sites, the relative importance of individual taxa to NMDS axes, and the degree of potential association among continuous site variables, water and soil chemistry, and leaf nutrient concentrations.

The optimal NMDS solution for macroinvertebrate taxa from GSL fringe wetlands yielded three (3) axes and a final stress of 0.16. A visual representation of the ordination, highlighting invertebrate taxa in NMDS 'species space' is shown in Figure 12. The ordination axes were rescaled and rotated such that the first axis (NMDS1) contains the greatest variation among sites in ordination 'species space'.

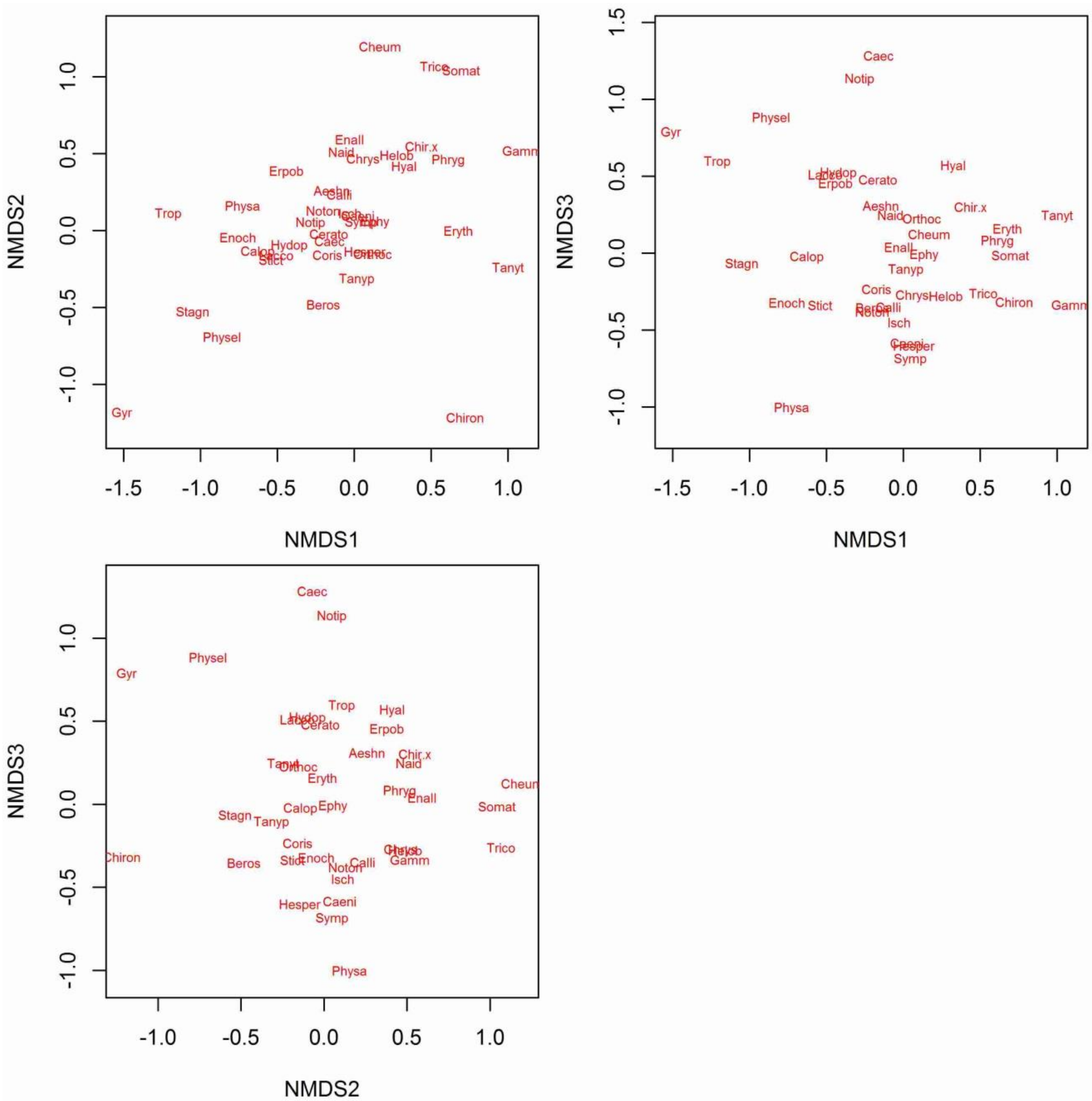

Figure 12. NMDS ordination of benthic macroinvertebrate taxa

Invertebrate taxa codes (red text, see Table 10) illustrate the distribution of taxa in NMDS ‘species space’.

Invertebrate Taxa

While overlap among invertebrate taxa, particularly towards the center of the axes in Figure 12, obscures some of the detail, there was modest evidence ($p<0.05$) that 9 out of 40 invertebrate taxa were associated with NMDS axes (Table 12). The abundance of five taxa were particularly associated with invertebrate community composition, with $p < 0.005$ and r^2 values > 0.16 (Table 12), including two midges (tribe *Tanytarsini* and *Chironomus*), a dragonfly (*Somatochlora*), a snail (*Physa*), and the amphipod (*Hyalella azteca*). An interpretation for any gradient or community patterns described by the relative abundance of these taxa is not readily available (at least based on taxa alone), however, it seems interesting that the two midges from the subfamily Chironominae were most clearly associated with orthogonal axes, suggesting that these two closely-related taxa groups occupy distinct portions of the overall invertebrate community of fringe wetlands.

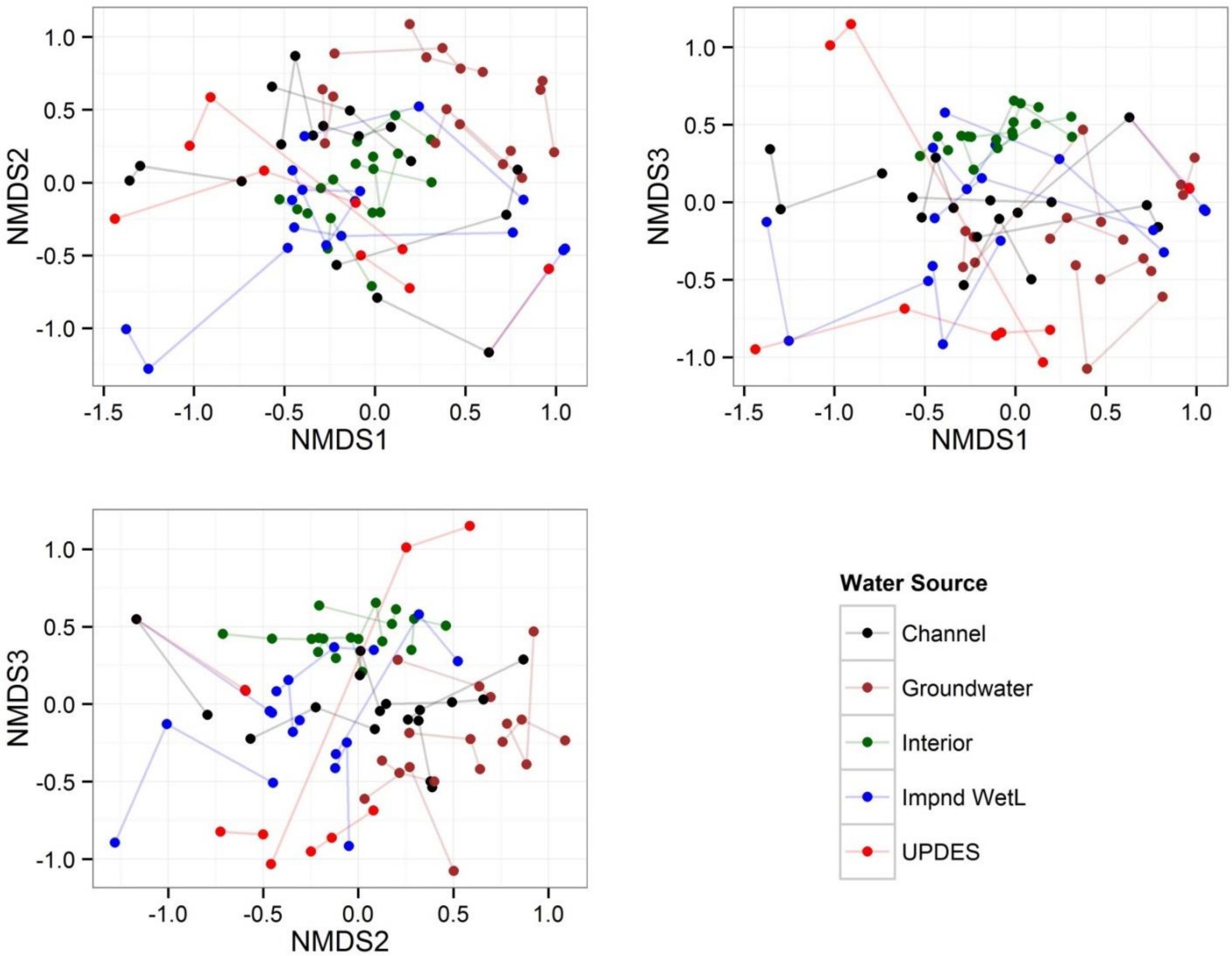

Figure 13. Macroinvertebrate NMDS Site Scores (by transect distance)

Site scores in invertebrate 'species space'. Solid circles are site x transect samples, shaded by dominant water source. Lines indicate within-site variation among invertebrate samples (by transect distance).

Environmental Site Factors

The distance in invertebrate community 'species space' among samples within a site (by distance along the main 'flowpath' transect) varied widely among sites. As shown in Figure 13, some sites had similar invertebrate communities across all samples (clusters of similarly-colored points joined by short lines) while other sites had strongly different communities (inferred from divergent ordination scores) among samples. In addition, groups of sites based on contributing watershed and dominant water sources, had significantly different ordination scores among groups ($p<0.001$ for both). For watersheds, sites from Utah's West Desert (Snake Valley sites) appeared to be most distinct from the GSL watersheds, based on axes 1 and 2. Similarly, sites receiving groundwater inflows were most distinct from the other groups, based on axes 1 and 2, while 'interior' wetlands were modestly distinct from the others along axis (Figure 14).

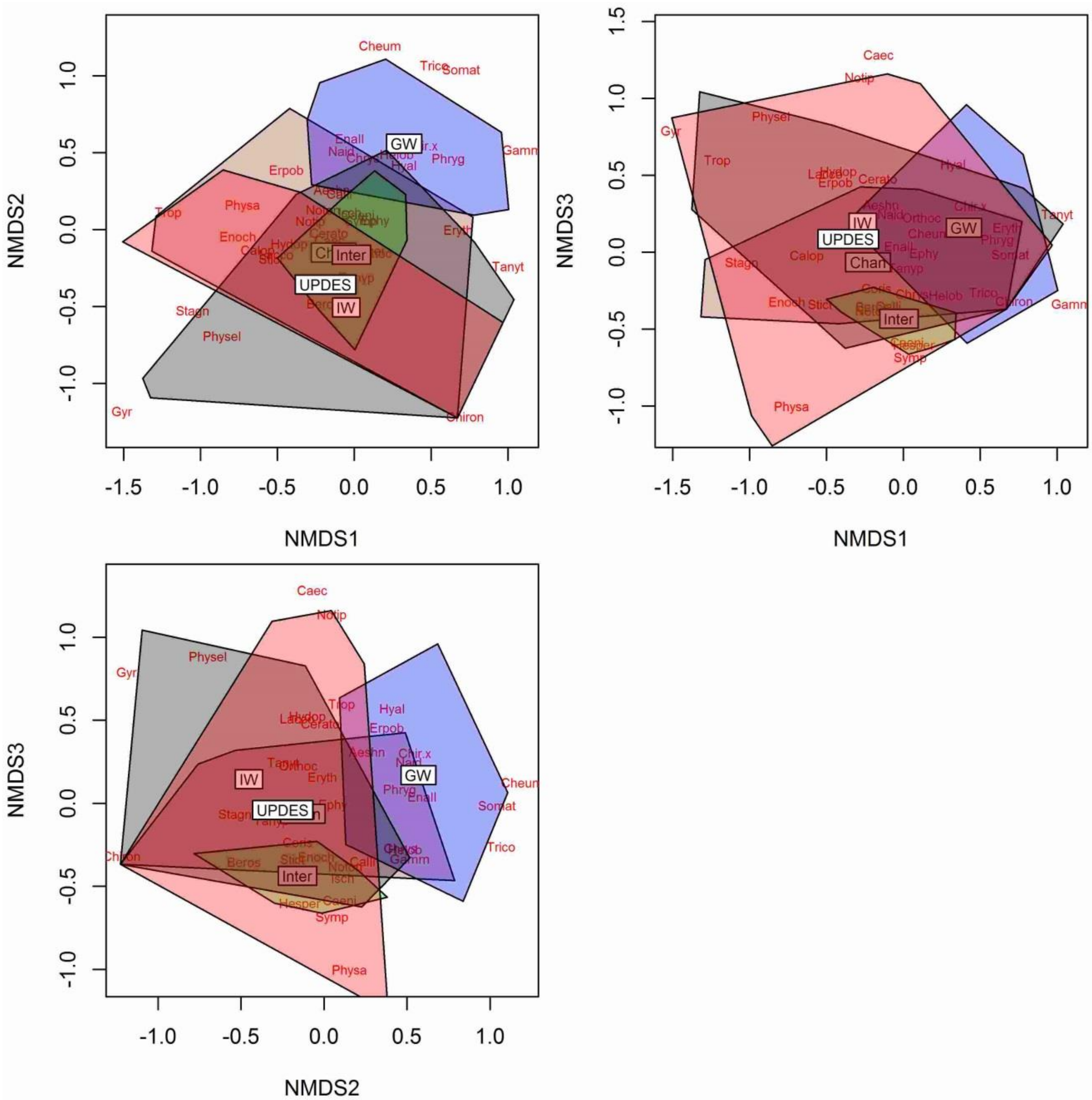

Figure 14. NMDS ordination of macroinvertebrate taxa

Invertebrate taxa codes (see Table 7) and convex hulls (shaded polygons) around dominant water sources for fringe wetland sites. Water sources coded as follows: GW = groundwater (blue); Inter = interior wetlands (green); IW = impounded wetlands (gray); UPDES = treated wastewater discharge (red); Chan = stream and canal channels (tan).

Table 12. Potential associations between macroinvertebrate taxa and Invertebrate-NMDS axis 1-3 scores.

Taxon Code	Taxa Name	Taxa Group	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit	
						(r^2)	(P)
Tanyt	*Tanytarsini*	Midge	1.017	-0.244	-0.137	0.212	0.002
Soma	*Somatochlora*	Dragonfly	0.680	1.058	-0.133	0.195	0.003
Physa	*Physa*	Snail	-0.769	0.313	0.945	0.180	0.004
Chiron	*Chironomus*	Midge	0.688	-1.155	0.512	0.172	0.003
Hyal	*Hyalella*	Amphipod	0.330	0.328	-0.634	0.164	0.002
Trico	*Tricorythodes*	Mayfly	0.497	1.101	0.104	0.130	0.014
Enoch	*Enochrus*	Aq. Beetle	-0.783	0.044	0.269	0.121	0.021
Trop	*Tropisternus*	Aq. Beetle	-1.180	-0.006	-0.693	0.114	0.022
Beros	*Berosus*	Aq. Beetle	-0.226	-0.394	0.431	0.101	0.044

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \leq 0.05$.

Invertebrate Community Metrics and Continuous Site Variables

There was modest evidence ($p<0.05$) that 3 of 4 invertebrate community metrics were associated with invertebrate community NMDS axes (Table 13; *lightly shaded rows*). Simpson's Diversity Index (1-D) and total invertebrate richness were associated with positive axis 2 scores, while invertebrate abundance was associated with negative axis 2 scores. An interpretation for increasing diversity along axis 2 is not entirely clear, however, the changes in invertebrate abundance appear to be associated with that for the common midge *Chironomus*.

We also found evidence that 7 of 10 site variables were associated with invertebrate NMDS axes (Table 13). The strongest associations occur for axes 2 and 3 (Figure 15), where a gradient in relative cover of invasive plant species versus total cover emergent vegetation increases along axis 2, and an apparent aquatic (submerged) to emergent habitat gradient occurs along axis 3. The relative importance of aquatic habitats and total cover of (raised) surface litter appear to be opposing forces acting on fringe wetland invertebrate community composition, possibly indicative of the quantity and/or quality of detritus that forms the basis of invertebrate food webs.

Table 13. Potential associations between Site Variables / Invertebrate Metrics vs. Invertebrate-NMDS scores.

Variable Code	Site Variable	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit	
					(r^2)	(P)
RelCov.INV	*Rel. Cover of Invasive Plants taxa*	0.008	-0.937	0.348	0.269	0.001
Sum.Aq	*Total Cover of Aquatic Plants*	-0.502	-0.339	-0.796	0.252	0.001
Litter.cov	*Total Cover of Surface Litter*	0.335	0.569	0.751	0.238	0.001
Em.Veg	*Total Cover of Emergent Vegetation*	0.031	0.870	0.492	0.224	0.001
Veg.Ht.cm	*Height of Dominant Veg. (cm)*	-0.031	-0.393	0.919	0.182	0.002
Simp.inv	*Simpson's Diversity Index (1-D)*	-0.089	0.953	-0.289	0.148	0.010
veg.BioVol	*Plant Biovolume (cover x height)*	-0.067	-0.211	0.975	0.143	0.007
Inv.Rich	*Total Invertebrate Richness*	-0.230	0.916	-0.328	0.140	0.011
Inv.Abund	*Total Invertebrate Abundance*	0.304	-0.931	-0.204	0.130	0.012
Water.z.cm	*Mean Water Depth (cm)*	-0.081	-0.885	-0.459	0.115	0.019

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \leq 0.05$. Invertebrate metrics are shaded light grey.

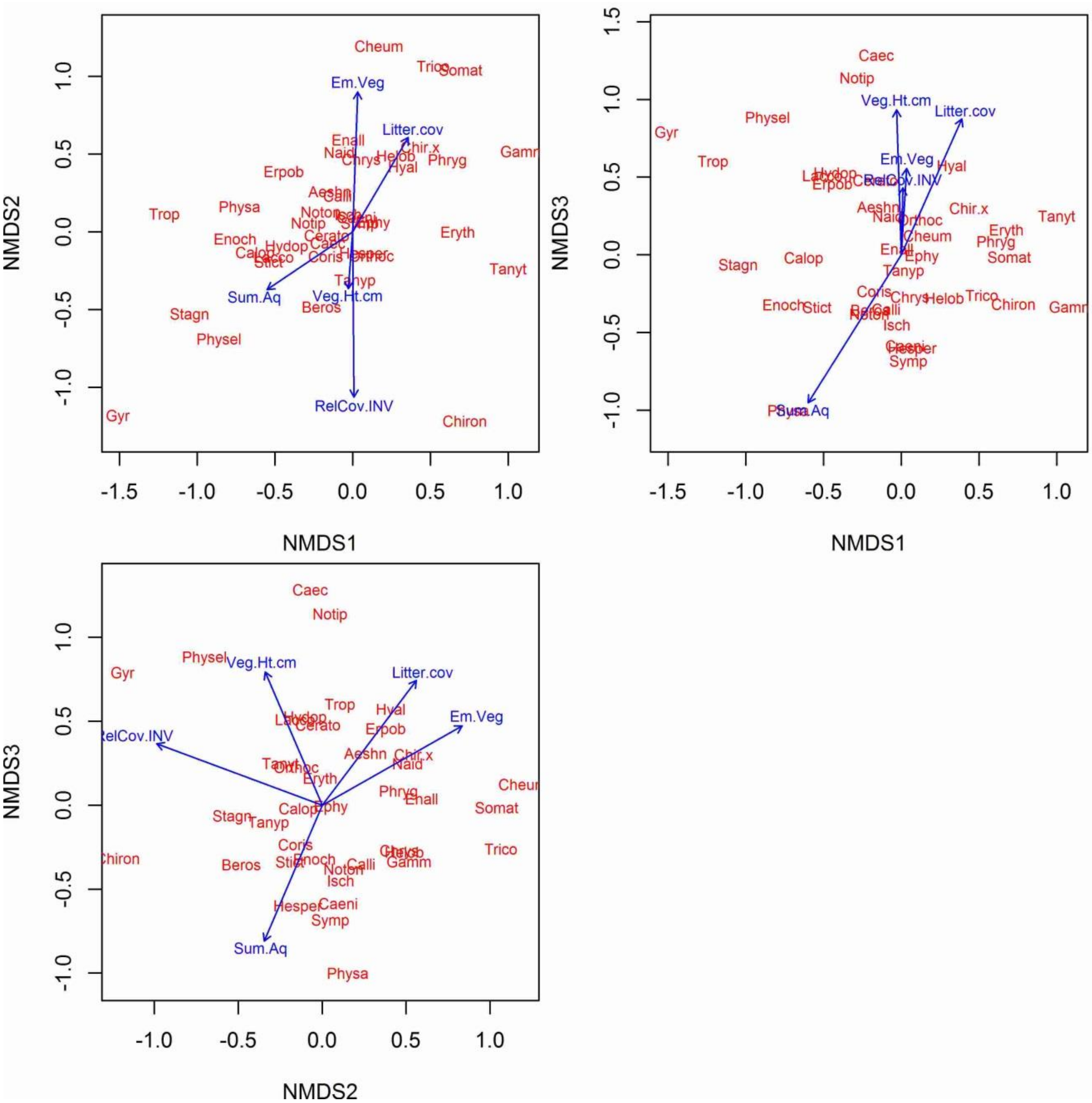

Figure 15. Invertebrate community NMDS ordination and significant environmental site variables

Water Chemistry

There was strong evidence ($p<0.005$) for an association between 8 of 53 water chemistry variables and invertebrate NMDS axes (Table 14). Negative axis 1 values were most strongly associated with Total Organic C (TOC) and Total Phosphorus (TP) concentrations in the water column, while low axis 2 scores were associated with temperature and total selenium concentrations (and greater abundance of *Chironomus*). Axis 3 scores appeared to describe a gradient from higher pH and water temperature to increasing Calcium and TP concentrations, and greater probability for an exceedance in undissociated hydrogen sulfide (H_2S) concentrations (also a consequence of lower pH).

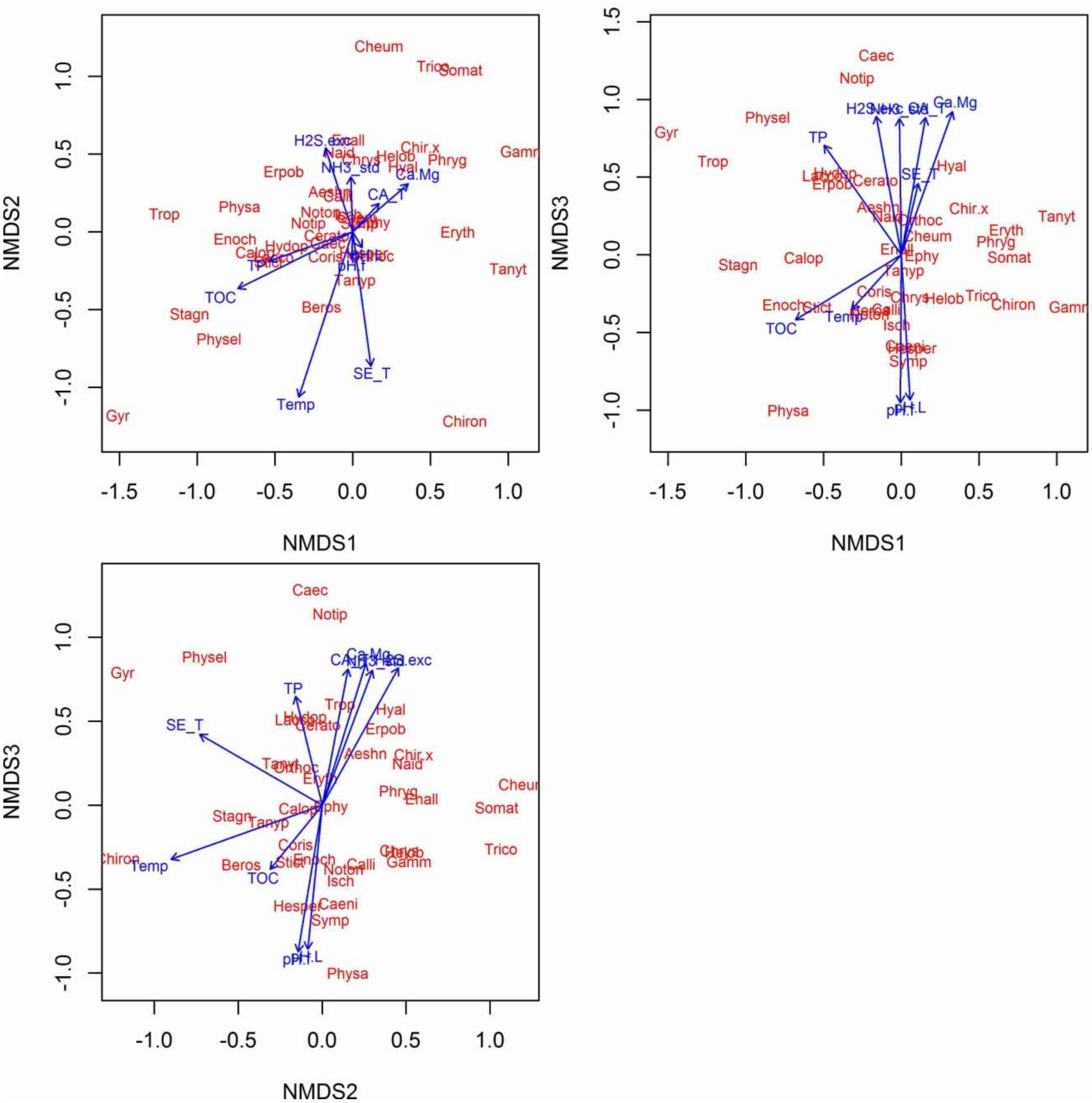

Figure 16. Invertebrate community NMDS ordination and significant water chemistry variables

Table 14. Potential associations between Water Chemistry and Invertebrate-NMDS axis 1-3 scores.

Variable Code	Site Variable	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit	
					(r^2)	(P)
Temp	*Water Temperature (C)*	-0.294	-0.900	-0.321	0.305	0.001
H2S.exc	*H_2S Exceedance (binary)*	-0.157	0.479	0.863	0.275	0.001
Ca.Mg	*Calcium to Magnesium ratio*	0.323	0.279	0.904	0.268	0.001
pH.f	*pH (field measure)*	-0.006	-0.162	-0.987	0.240	0.001
SE_T	*Total Selenium (ug/L)*	0.117	-0.860	0.497	0.221	0.002
CA_T	*Total Calcium (mg/L)*	0.170	0.183	0.968	0.214	0.002
TP	*Total Phosphorus (mg/L)*	-0.564	-0.196	0.802	0.199	0.004
TOC	*Total Organic C (mg/L)*	-0.786	-0.390	-0.480	0.193	0.001

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \leq 0.005$.

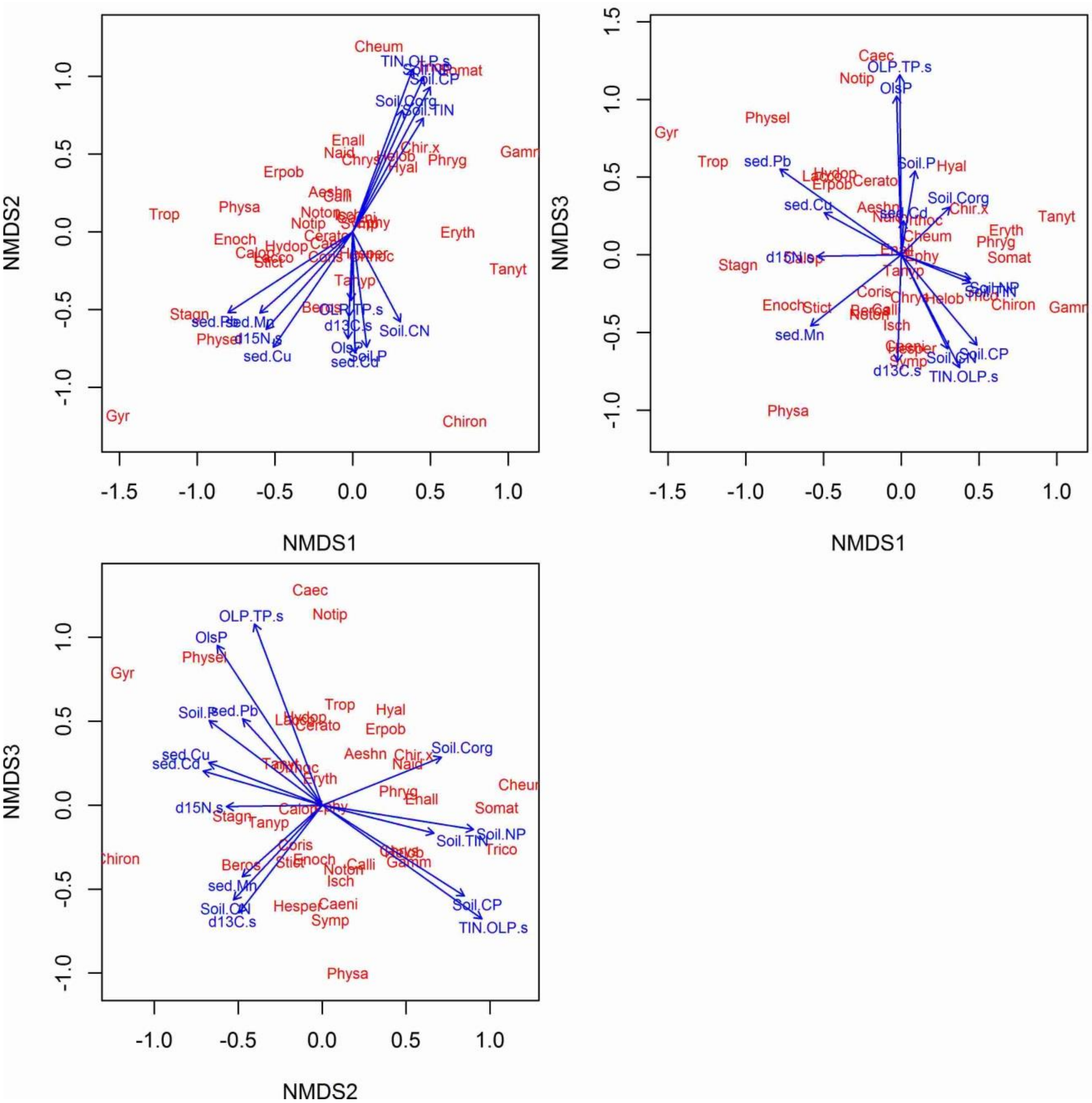

Figure 17. Invertebrate community NMDS ordination and significant soil chemistry variables

Soil Chemistry

There was modest evidence ($p<0.01$) for an association between 18 of 29 soil chemistry variables and invertebrate NMDS axes (Table 15). In a pattern quite similar to that for soil chemistry and plant community composition, three sets of highly correlated soil chemistry variables appear to be associated with invertebrate NMDS axes 1 and 2 (Figure 17). One set includes soil organic C and total inorganic N (TIN) concentrations, and soil C:P and TIN to Total P ratios along positive portions of axes 1 and 2, suggesting a gradient of increasing N availability. A second set includes soil Cu, Pb, and Mn concentrations and soil δ^{15}N stable isotope signatures along negative portions of both axis 1 and 2, however, a link between increasing δ^{15}N and metals concentrations in unclear. A third set includes soil P, Olsen-P, total C δ^{13}C stable isotope ratios, and soil NP ratios along negative portions of axis 2 and neutral to slightly positive portions of axis 1, suggesting a soil carbonate and P gradient. These variables sets appear more continuous after the third NMDS axis is considered, suggesting a complex suite of soil gradients within fringe wetlands. Interestingly, soil salinity (as specific conductivity from 1:2 soil:water mixtures) was not significantly associated with any of the invertebrate NMDS axes.

Table 15. Potential associations between Soil Chemistry and Invertebrate-NMDS axis 1-3 scores.

Variable Code	Site Variable	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit	
					(r^2)	(P)
TIN.OLP.s	*Soil TIN to Olsen-P ratio*	0.29	0.78	0.29	0.489	0.001
OLP.TP.s	*Soil Olsen-P to Total P ratio*	-0.01	-0.35	-0.01	0.438	0.001
OlsP	*Soil Olsen-P (mg/kg)*	-0.02	-0.55	-0.02	0.429	0.001
Soil.CP	*Soil Total C to Total P ratio*	0.41	0.77	0.41	0.400	0.001
sed.Pb	*Soil Lead (mg/kg)*	-0.72	-0.47	-0.72	0.336	0.001
Soil.NP	*Soil Total N to Total P ratio*	0.41	0.90	0.41	0.331	0.001
sed.Cu	*Soil Copper (mg/kg)*	-0.54	-0.79	-0.54	0.242	0.001
Soil.P	*Soil Total P (mg/kg)*	0.10	-0.80	0.10	0.236	0.001
sed.Mn	*Soil Manganese (mg/kg)*	-0.65	-0.57	-0.65	0.232	0.001
Soil.CN	*Soil Total C to Total N ratio*	0.34	-0.64	0.34	0.222	0.001
Soil.Corg	*Soil Total Organic C (g/kg)*	0.36	0.87	0.36	0.222	0.001
d13C.s	*Soil δ^{13}C signature (o/oo)*	-0.03	-0.61	-0.03	0.216	0.001
Soil.TIN	*Soil Total Inorganic N (mg/kg)*	0.52	0.83	0.52	0.211	0.001
Soil.C	*Soil Total C (g/kg)*	0.58	0.81	0.58	0.193	0.002
d15N.s	*Soil δ^{15}N signature (o/oo)*	-0.66	-0.75	-0.66	0.191	0.001
sed.Cd	*Soil Cadmium (mg/kg)*	0.02	-0.96	0.02	0.179	0.001
sed.Ba	*Soil Barium (mg/kg)*	0.21	-0.01	0.21	0.159	0.002
Soil.N	*Soil N (g/kg)*	0.37	0.79	0.37	0.157	0.006
sed.THg.ppb	*Soil Total Mercury (ug/kg)*	-0.72	-0.67	-0.72	0.155	0.003

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \leq 0.01$.

Table 16. Potential associations between Leaf Nutrient Chemistry and Invertebrate-NMDS axis 1-3 scores.

Variable Code	Site Variable	Axis 1 Score	Axis 2 Score	Axis 3 Score	Vector Fit	
					(r^2)	(P)
Veg.CP	*Leaf C to P ratio*	0.215	0.905	-0.367	0.417	0.001
Veg.CN	*Leaf C to N ratio*	0.494	0.809	0.320	0.416	0.001
Veg.N	*Leaf N (g/kg)*	-0.457	-0.883	-0.105	0.401	0.001
Veg.P	*Leaf P (k/kg)*	-0.054	-0.707	0.705	0.347	0.001
Veg.NP	*Leaf N to P ratio*	-0.038	0.763	-0.645	0.316	0.001
Veg.C	*Leaf C (g/kg)*	-0.085	-0.440	0.894	0.244	0.001
d15N	*Leaf δ^{15}N signature (o/oo)*	-0.316	-0.803	0.505	0.162	0.007

Strength of association based on Pearson's (r) statistic, for variables with vector significant at $p \leq 0.01$.

There was modest evidence ($p<0.01$) for an association between 7 of 8 leaf nutrient chemistry variables and invertebrate NMDS axes (Table 16). The largest effects of leaf nutrient status appear to vary along NMDS axis 2, with increasing leaf C:nutrient and N:P ratios at higher axis values and increasing leaf N and P concentrations toward lower (negative) axis 2 values.

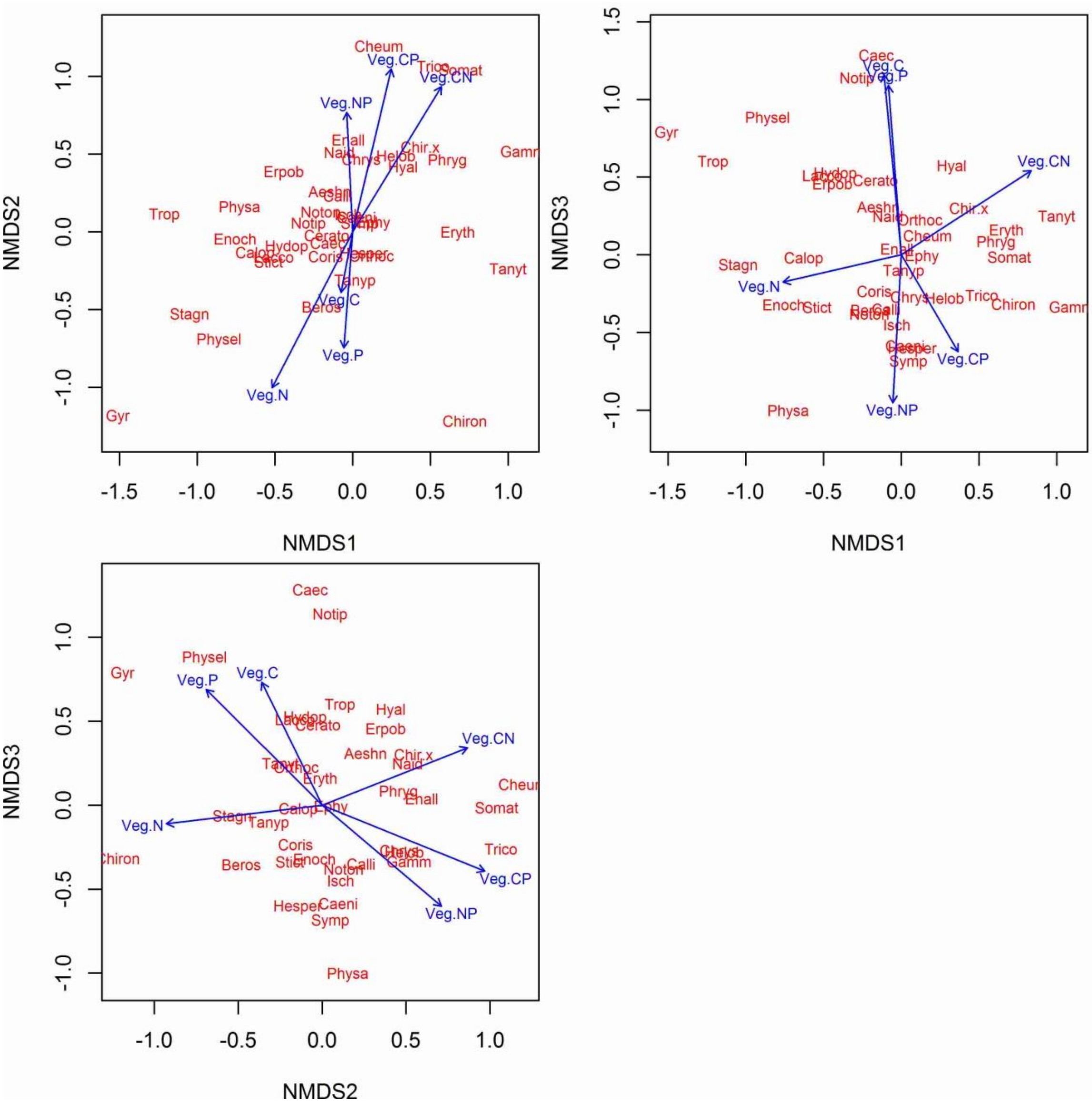

Figure 18. Invertebrate community NMDS ordination and significant leaf chemistry variables

4.3 Water Chemistry

The aquatic features of Great Salt Lake fringe wetlands vary from small, nearly isolated patches of water amongst dense emergent vegetation to extensive open water areas containing submerged vegetation and mats of benthic periphyton. Our objective was to characterize the overall chemical environment of surface waters that serve as both inputs and losses of constituents to the wetland. Summary statistics for 40 measured and derived water quality variables are shown in Table 17. This table includes benchmarks for a subset of analytes, including numeric criteria as appropriate, as context for interpreting these data.

Standard Water Quality Parameters

Standard water quality parameters describe the general physical and chemical conditions related to aquatic metabolism in surface waters, and include: temperature, pH, specific conductance, dissolved O_2, total suspended solids and chlorophyll-a. (Table 17). While most samples were generally within the expected range for standard water quality parameters from GSL wetlands (DWQ, 2015), up to 20% of water temperature observations (from daytime grab samples) exceeded numeric criteria for warm water (3B) or non-game (3C) fisheries. Most of the high temperatures (19 of 21) were from fringe wetlands within Farmington Bay (interior wetlands), or below shallow impounded wetlands with little emergent cover, while cooler waters were observed below discharge from UPDES or groundwater sources. In addition, 17 water samples had pH in excess of the 9.0 criteria for aquatic life (*Link*) and 16 samples had pH below 3.0 mg O_2/L. High pH values were most common in areas with predominantly aquatic versus emergent vegetation, warmer temperatures and total alkalinity below approximately 300 mg $CaCO_3$/L. In contrast, low DO concentrations were most commonly observed in dense stands of emergent vegetation downstream of nutrient-enriched water sources. Chlorophyll-a concentrations range from below reporting limits to over 50 µg/L. Highest chlorophyll-a concentrations were observed in waters with the highest total nutrient concentrations (which is expected, since floating algal cells are included in total nutrient measurements). Interestingly, sites with chlorophyll-a greater than 50 µg/L tended to have lower cover of aquatic vegetation, shallow water depths (< 9 cm) , higher emergent cover and wide range of surface water cover. However, enhanced productivity in fringe wetlands resulting from site disturbance or nutrient enrichment can result in a wide array of biological responses beyond increases in water column chlorophyll-a concentrations, including increased growth of emergent vegetation and development of surface mats of filamentous algae. *These measures of plant (and algal) productivity will need to be integrated to better understand how fringe wetlands respond to nutrient enrichment*.

Nutrients and Organic Matter

Concentrations of nutrients and detrital organic matter within the water column ranged widely among samples (and sites), where the range in observed values was several times greater than median values (Table 17). While lower quartiles (25th percentile) for inorganic N species (NH_4^+, NO_3^-) and total N were similar to values for impounded wetlands adjacent to Great Salt Lake, the lower quartile for total (digested) P was 2 times higher in fringe vs. impounded wetlands (DWQ, 2015). Among distinct wetland types, the largest differences were found along the upper quartile (75th percentile), where concentrations in fringe wetlands were lower for NH_4^+ but higher for NO_3^-, total N, organic N, organic C, and total P compared to impounded wetlands. Total inorganic N (TIN) accounted for 3 to 54% of total N (upper and lower quartiles) in the water column, compared to 5 to 15% in impounded wetlands (DWQ, 2015). In general, lower TIN:TN ratios (i.e. greater contribution of organic versus inorganic N to total N pools) suggest greater biotic processing of available nutrients, via uptake and retention.

Of the 102 water samples collected, only three (3) had NO_3^- concentrations greater than the 'pollution indicator' benchmark of 4.0 mg N/L (Table 17). Similarly, six (6) samples exceeded the benchmark for NH_3 toxicity, based

Table 17. Summary Characteristics of Water Chemistry Parameters for Fringe Wetlands

Parameter	Units	MRL	Samples below MRL	Number of Obs	Percentiles *					Range	Samples Exceeding	Benchmark	Comments
					10th	25th	Median	75th	90th				
Standard Water Quality Parameters													
Temperature	° C	-		102	17.38	19.84	22.28	26.21	31.22	23.47	21	27	Criterion for warm water fishery (3B) or non-game fishery (3C)
pH	-	-		102	7.31	7.71	8.13	8.78	9.25	2.89	17	<6.5 or >9.0	See Note [1]
Specific Conductance	µS/cm	-		102	781	1314	2980	4403	10,139	16,680	13	7,500	Tolerance for freshwater marsh (See Keate, 2005)
Total Dissolved Solutes (TDS)	mg/L	10	0	102	451	771	1696	2634	5819	10,926			
Dissolved O_2	mg O_2/L	-		97	1.43	4.23	7.09	9.29	14.8	25.35	16	3.0	See Note [1]; Exceedance refers to DO concentrations *below* the benchmark.
Dissolved O_2	% sat	-		97	20.7	55.1	91.8	128.1	212.7	413.1			
Suspended Solids, total (TSS)	mg/L	4	12	102	2.0	7.6	42.4	124	635	5978			
Volatile Solids, total (TVS)	mg/L	4	25	102	2.0	3.5	11.8	33.6	145.4	3828			
TVS:TSS ratio	(mass ratio)	-		102	0.14	0.20	0.32	0.65	1.00	0.90			
Chlorophyll-a	µg/L	1.3	54	102	2.0	2.7	8.6	26.7	57.7	212			MRL varies with filtration volume, analytical detection limit is currently 2.0 µg
Nutrient and Organic Matter Concentrations													
Ammonium (NH_4)-N, total	mg N/L	0.02	39	102	0.01	0.01	0.03	0.09	1.21	4.19	6	1.193	See Notes [1] and [2]. Benchmark shown is based on the median values for pH and Temp (pH 7.6 and Temp 23.2 °C), for ammonia toxicity.
Nitrate + Nitrite (NO_3 + NO_2)-N, total	mg N/L	0.1	25	102	0.008	0.009	0.04	0.56	2.24	11.30	3	[4.0]	See Note [3]. MRL was 0.1 in 2013 and 0.015 in 2015
Organic N, total	mg N/L	-		102	0.18	0.55	1.0	2.2	3.5	25.5			
Total N, total	mg N/L	0.2	1	102	0.23	0.83	1.79	3.17	6.02	28.3			
Phosphorus, total (digested)	mg P/L	0.02	1	102	0.014	0.114	0.240	0.83	2.68	14.80	81	[0.05]	See Note [4].
TN:TP ratio	(mass ratio)	-		102	1.4	2.7	6.4	18.2	28.8	91.1			
Organic Carbon, total	mg C/L	0.5		102	1.0	6.2	10.1	23.9	39.3	64.1			
TOC:TON ratio	(mass ratio)	-		102	4.5	6.5	11.1	13.1	14.3	50.6			
Major Anion and Cation Concentrations													
Sulfate (SO_4)	mg S/L	20	0	102	47.8	57.5	71.3	172.5	256.5	355.2			
Chloride (Cl)	mg Cl/L	1	0	102	74.6	156	723	1,115	2,467	5438			
Flouride (F)	mg F/L	0.5	25	102	0.33	0.50	0.62	0.90	1.14	2.4			MRL is sensitive to salinity (samples require dilution)
Calcium (Ca)	mg Ca/L	1		102	40.5	57.8	67.7	76.5	138.8	297.8			
Magnesium (Mg)	mg Mg/L	1		102	29.8	40.0	54.5	72.2	123.7	165.6			
Potassium (K)	mg K/L	1		102	6.1	11.2	26.1	40.0	83.8	123.7			
Sodium (Na)	mg Na/L	1		102	58.1	124	388	752	1832	2783			
Iron (Fe)	mg Fe/L	0.02	28	91	0.05	0.08	0.15	0.80	1.81	30.5	17	1.0	See Note [1]. MRL is sensitive to salinity.
Manganese (Mn)	mg Mn/L	0.005	20	102	0.003	0.008	0.036	0.104	0.262	6.10	34	0.08	See Note [7].
Hardness, total (as $CaCO_3$)	mg $CaCO_3$/L			102	284	334	385	485	740	1,193			
Trace Metal Concentrations													
Aluminum, total (Al)	µg Al/L	10	11	102	5.0	27.9	95.3	442.3	1,056	30,135	19	750	See Note [1]; acute value.
Arsenic, total (As)	µg As/L	1		102	4.13	5.57	8.61	11.94	25.31	59.5	-	340	See Note [1]; acute value.
Barium, total (Ba)	mg Ba/L	0.1	47	102	0.05	0.05	0.1	0.15	0.24	1.2	1	1.0	See Note [5].
Cadmium, total (Cd)	µg Cd/L	0.1	83	102	0.05	0.05	0.05	0.10	0.25	2.4	1 / 0	0.62 / 7.37	See Notes [1] and [6]. Benchmarks shown are median of calculated site values. MRL sensitive to salinity
Copper, total (Cu)	µg Cu/L	1	15	102	0.50	2.42	5.36	8.35	25.3	2,887	2 / 2	28.3 / 47.9	See Notes [1] and [6]. Benchmarks shown are median of calculated site values.
Chromium, total (Cr)	µg Cr/L	2	55	72	1.0	1.0	1.0	1.0	3.19	4.2	0 / 0	224 / 1,720	See Notes [1] and [6]. Benchmarks shown are median of calculated site values.
Nickel, total (Ni)	µg Ni/L	5	92	102	2.5	2.5	2.5	2.5	4.11	62.5	- / -	162.8 / 1466	See Notes [1] and [6]. Benchmarks shown are median of calculated site values.
Lead, total (Pb)	µg Pb/L	0.1	20	102	0.05	0.17	1.25	3.27	7.39	93.5	6 / 0	9.6 / 246.1	See Notes [1] and [6]. Benchmarks shown are median of calculated site values.
Selenium, total (Se)	µg Se/L	1	67	102	0.5	0.5	0.5	1.08	1.75	5.4	1 / 0	4.6 / 18.4	See Note [1].
Mercury, total (THg)	µg THg/L	0.2	98	102	0.1	0.1	0.1	0.1	0.1	0.13	102	0.012	See Note [1]. Note that screening level is 8x lower than MRL.
Zinc, total (Zn)	µg Zn/L	10	71	102	5.0	5.0	5.0	13.1	59.2	1,206	3 / -	370.6	See Notes [1] and [6]; acute and chronic values are equivalent.
Toxic Ligands													
Hydrogen Sulfide, total (H_2S)	mg S/L	0.1	86	102	0.05	0.05	0.05	0.05	0.14	1.76	63	0.002	See Note [1]; criterion is function of pH (see Note [8].

Notes: [*] 30 samples were collected for each parameter; 3 locations from 10 sites.
[1] See R317.2, Table 2.14.2 for Aquatic Wildlife Use (3D).
[2] For ammonia toxicity, chronic criteria is a function of both pH and temperature.
[3] Nitrate listed as a pollution indicator in R317.2, Table 2.14.2 for Aquatic Wildlife Use, but no value provided for use class 3D. Wildlife use classes 3B (warm water fish) and 3C (non-game fish) have value of 4.0.
[4] Total phosphorus listed as pollution indicator in R317.2, Table 2.14.2 for Aquatic Wildlife Use (3B) value of 0.05; value for lakes and reservoirs is 0.025.
[5] See R317.2, Table 2.14.1 for Human Health Use (1C); no value for Aquatic Wildlife.
[6] First value is total recoverable value for chronic criteria, corrected for hardness; second value is acute value (also corrected).
[7] Value is from Screening Quick Reference Tables (SQuiRT) for surface water (FW) (see: Link to NOAA).
[8] The proportion of undissociated $H_2S_{(aq)}$ from total hydrogen sulfide (measured value) was calculated from a thermodynamic model at 25 °C under freshwater conditions (ionic strength of 0.05 mM), and fitted to a sigmoidal curve: $H_2S_{(aq)}/H_2S_{total} = 1 - \left[1/\left(1 + e^{-\left((pH-\beta_0)/\beta_1\right)}\right)\right]$; where β_0 = 7.018, and β_1 = 0.434, estimates of the mean and standard deviation of 50 data points for pH from 4.0 to 10.0.

on the chronic criteria for aquatic life use. In addition, 81 samples had total P concentrations greater than the 0.05 benchmark. Based solely on the number of samples exceeding these nutrient benchmarks, it would appear that total P concentrations are relatively more enriched than NH_4^+ or NO_3^-.

The stoichiometry of total organic C, N, and P pools within the water column can provide evidence on sources of organic matter inputs, the degree of processing, as well as the relative abundance of available nutrients to the base of aquatic food webs. However, measurements were made on total, i.e. unfiltered, water samples and should be interpreted with care, as increasing quantities of phytoplankton and suspended detritus (as described for chlorophyll-a concentrations in the previous section) can drive nutrient ratios toward that of particulate organic matter. Nonetheless, TOC to TON ratios ranged from 4.5 to 14.3 (10^{th} to 90^{th} percentiles), protoplasm derived from heterotrophic bacteria and/or algae from high-nutrient conditions versus an increasing proportion of detritus derived from emergent vegetation, respectively. Total N to TP ratios (by mass) ranged from 1.4 to over 28 (10^{th} to 90^{th} percentiles). Narrow TN:TP ratios, below approximately 3.5 by mass (equivalent to 8:1 molar ratios) are indicative of high P vs. N availability (also called N-limited), while ratios above 11 (24:1 molar ratio) suggest greater N availability vs. P availability (or P limitation) to the growth of primary producers. As such, the surface waters of fringe wetlands represent a vast range in the relative availability of N and P.

Since nearly all benchmarks in Table 17 were developed for freshwater systems, the extent to which these criteria have functional significance on the relative health of fringe wetlands is unclear, particularly for very slowly flowing areas dominated by emergent marsh. Interestingly, soluble organic N represents a clear majority of the total N pool within the waters of 75% of fringe wetland samples, supporting the idea that many wetlands function as nutrient and biomass 'transformers' from inorganic to organic forms.

Major Anion and Cations

Across all samples, the concentrations of major ions ranged from 450 to over 10,000 mg/L (TDS) (Table 17). Dominant cations were Na^+, Mg^{2+}, Ca^{2+}, and K^+, while the dominant anions were Cl^-, SO_4^{2-}, and HCO_3^- (estimated from total alkalinity). Na^+ and Cl^- ions were nearly always the dominant ions. The relative abundance of major ions (adjusted for charge differences) from surface waters of these fringe wetlands varied widely among sites and among dominant water sources (Figure 19). For example, wetlands receiving water from impounded wetlands had lower proportions of Ca^{2+} + Mg^{2+} vs. Na^+, and lower alkalinity (as HCO_3^-), relative to sites downstream of wastewater treatment plants and sites receiving groundwater discharge. Waters of interior wetlands were strongly dominated by Na^+/K^+ and Cl^-, reflecting the influence of GSL chemistry. Sites with urban or suburban influences (e.g. receiving waters from WWTPs, suburban streams, or the Jordan river) had higher Ca/Mg vs. Na ratios, however, other factors could be driving this pattern. The relative composition of major ions varied with the quantity of dissolved ions (as TDS)(*not shown*), increasing Na^+ and Cl^- relative to Ca^{2+}, Mg^{2+}, and HCO_3^-, with a plateau of approximately 15% Ca^{2+} + Mg^{2+} for TDS greater than 6,000 mg/L. Hardness of surface waters, based on Ca and Mg, was high relative to other nearby aquatic systems, ranging from < 300 to over 700 mg $CaCO_3$/L.

Concentrations of other major ions, including F and Fe, were typically low; however, 17 samples had Fe concentrations greater than the benchmark of 1.0 mg Fe/L (Table 17). Interestingly, high concentrations of Mn were observed in 34 of 102 samples, where Mn was a substantial contribution (over 30%) to major cation concentrations. Since these samples were unfiltered, it is possible that small and easily digestible flocc contributed to high Mn values; this idea is supported by higher TSS (600 mg/L) in samples with high Mn values compared to lower Mn samples (96 mg/L TSS). This observation points to the wide range of conditions within marsh wetlands, including a variable potential for Mn-sorption of heavy metals since the redox state can vary widely at small, moderate, and large spatial scales, and Mn solubility is strongly tied to redox of soils and overlying waters.

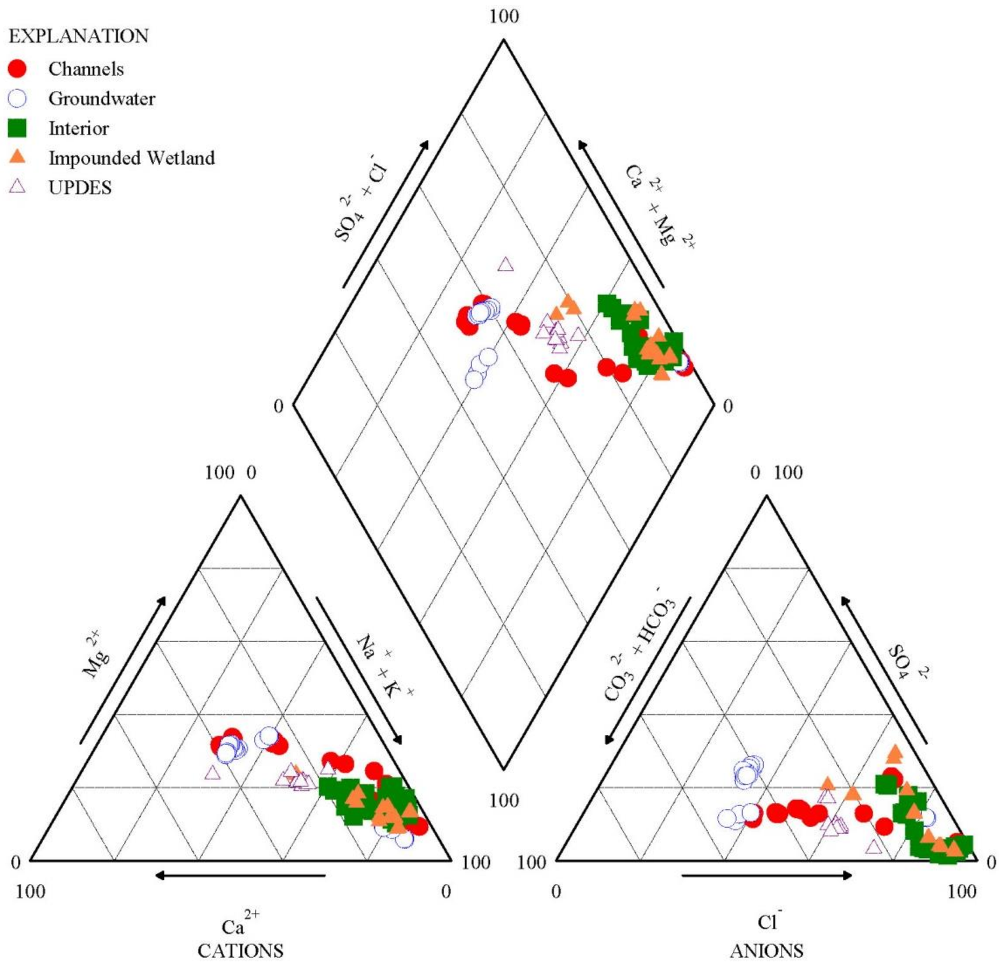

Figure 19. Major ions of Fringe Wetlands, by dominant water source.

Trace Metals (and metalloids)

Concentrations of several trace metals in surface waters ranged from less than laboratory reporting limits to values that (rarely) exceed acute benchmarks aquatic wildlife use (Table 17). Once again, it is important to note that only total (unfiltered) samples were collected for analyses of metal concentrations during this study, while the numeric criteria as described for the *dissolved fraction*. Even though conversion factors may be used to translate dissolved to total metals concentrations, and *vice versa*, these conversions are mainly used to establish and evaluate discharge permit limits. As such, these concentrations should be interpreted with caution.

DWQ continues to engage with partner laboratories in an effort to optimize analytical sensitivity against sample analysis cost, particularly where factors such as salinity may degrade instrument sensitivity, either by sample dilution or measurement interference, such as in wetlands adjacent to Great Salt Lake. Six trace metals had more than 50% of samples below the reporting limit, while total Mercury (THg) had reporting limits that exceeded the benchmark value. A reasonable goal going forward is for laboratory minimum reporting limits (MRLs) to be at least an order of magnitude lower than the lowest benchmark or screening level.

Aluminum was most commonly observed to exceed the wildlife use benchmark shown in Table 17, and Cu, Pb and Zn had at least two samples with concentrations higher than benchmarks. Benchmarks for six metals (Cd, Cu, Cr, Ni, Pb, and Zn), based on aquatic wildlife uses in Table 17, are calculated as a function of water hardness and the numeric criteria increases as hardness increases, up to a maximum value (at 400 mg/L); over 25% of fringe wetland samples had hardness > 400 mg/L suggesting the these systems have a chemical background that is protective for aquatic life.

Toxic Ligands

Lastly, the production and consumption of hydrogen sulfide (H_2S) is an important component of partially reducing environments in wetlands, since H_2S is a potentially toxic ligand to aquatic life. Calculation of the benchmark value requires measurement of pH *in situ* (similar to NH_4^+ benchmark (as NH_3)). shown in Table 17, many H_2S samples from fringe wetlands were both lower than the standard reporting limit for this analyte and higher than the aquatic wildlife benchmark. A field metric for the presence of sulfidic odor from wetland soils (following the US Army Corps of Engineers *Wetland Delineation* protocols) was used in 2015; 62% of samples with dissolved H_2S greater than the criterion had positive sulfidic odor from soils, however, this measurement was inconsistently applied and will need to be calibrated over a wider set of sites. Additional work on the presence of H_2S in wetland soils as well as laboratory refinements will continue to examine the significance and controls on H_2S levels within the water column of wetlands.

4.4 Supplemental Indicators

4.4.1 Wetland Soils

Soils encountered within these fringe wetland sites varied across a range of soil moisture (moist to severely inundated), particle size (gravelly loam to silty clay), and substrate (mucky peat to mineral) conditions. At the current time, laboratory protocols for several important wetland-soil characteristics are being worked out in collaboration with collaborators from Utah State University and the University of Utah, in an effort to build on water quality characteristics that apply to wetlands. These measurements include: soil total and extractable P, soil salinity, organic matter content, plant C, N and P concentrations, and plant and soil stable $\delta^{13}C$ and $\delta^{15}N$ signatures, and trace metals in soils and plant tissues

4.4.1.1 Soil extractable nutrients and total organic matter pools

Soil moisture content ranged from moist (0.30 g H_2O/g soil) to supersaturated (over 2.0 g H_2O/g soil) in submerged soils, indicative of the wide variety of environments within and among the fringe wetlands samples here. Extractable NH_4^+ and NO_3^- pools were combined as soil Total Inorganic N (TIN)(Table 18), because of some uncertainty in sample handling for a portion of sites (freezer failure and an extended time-period for sample processing) that may have affected the relative proportions of NH_4^+ vs NO_3^-. Since all soil samples were initially frozen prior to lab preparation, the combined inorganic N pool likely represents a freeze/thaw-labile fraction of N in addition to exchangeable inorganic N on soil surfaces. Variation in soil TIN concentrations among sites are shown in Figure 20 (bottom panel; sites are arranged alphabetically by dominant water source). Interestingly, sites with groundwater as the dominant water source had the largest pools of extractable TIN, occasionally exceeding 200 mg N/kg; sites with other water sources had TIN most commonly below 50 mg/kg (Table 18).

Olsen-P was used as an estimate of the labile P pool (0.1 M bicarbonate extract). Highest Olsen-P concentrations were found in sites below UPDES, IW and Channel water sources (Figure 20), with values often exceeding 100 mg P/kg. Sites receiving groundwater, as well as sites within the larger Willard Spur and Farmington Bay wetlands ('Interior' wetlands), had the lowest Olsen-P pools. These differences describe a gradient in N vs. P availability (as TIN vs. Olsen-P), from high N (high TIN:Olsen-P ratio) in groundwater-fed sites to high P (low TIN:Olsen-P ratios) in UPDES, IW, and some channel sites.

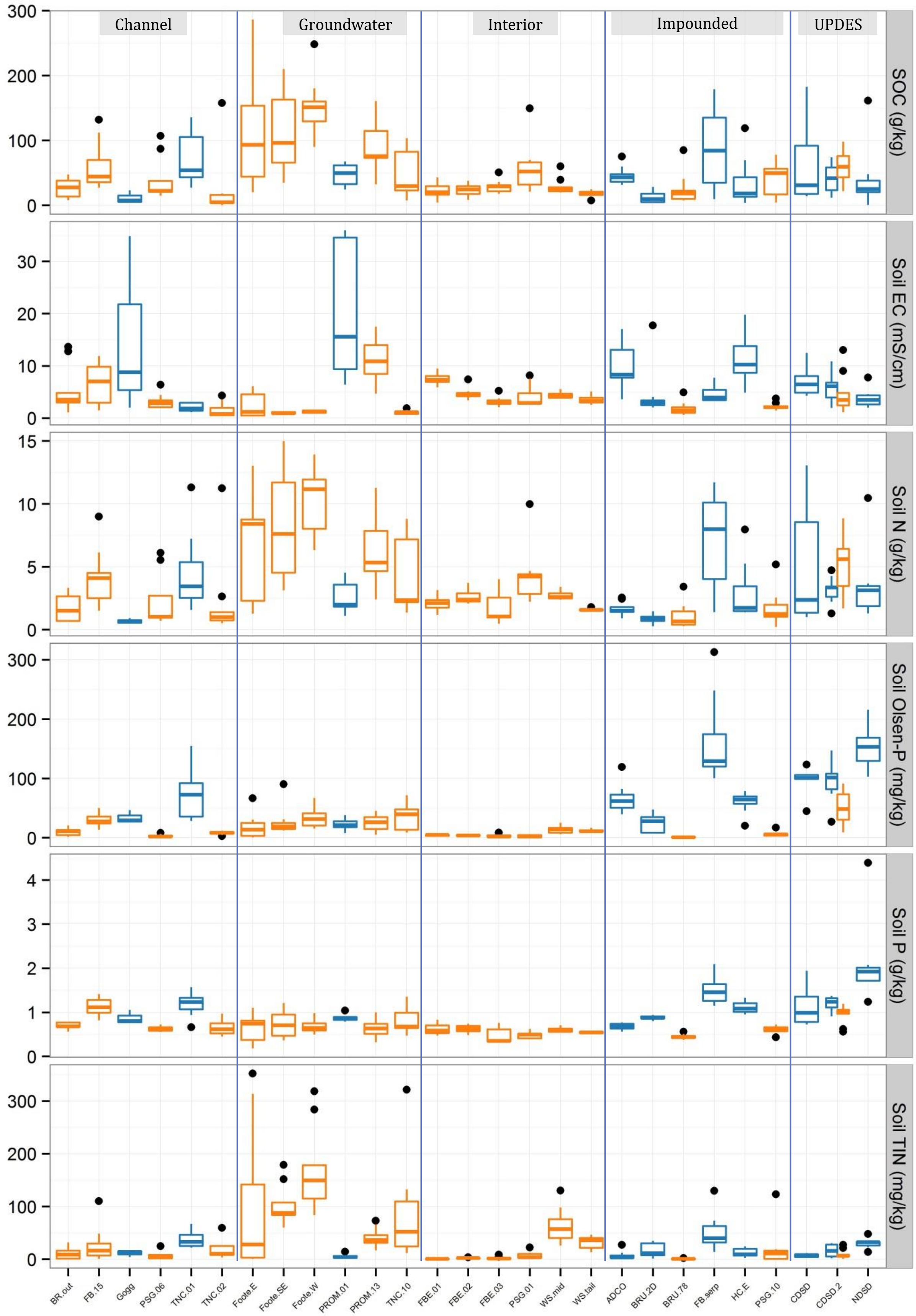

Figure 20. Distribution of key soil parameters across sites.

The distribution of soil organic C (SOC), total N (Soil N), and total P (Soil P) concentrations are shown Figure 20. SOC ranged from low values (< 70 g/kg) indicative of mineral soils in more open, aquatic bed and hemi-marsh Interior wetlands, to higher values (> 100 g/kg) indicative of organic C accumulation in mucky soils of groundwater-fed marshes. SOC was strongly correlated with total C, accounting for 75% of total C (r^2=0.77). Similarly, soil N increased with both SOC (r^2=0.87) and total C (r^2=0.84), and were highest in groundwater-fed wetlands or a few sites below impounded wetlands (FBSerp) or UPDES treatment facilities (CDSD). The latter two sites have thick accumulations mucky peat in association with dense stands of *Typha* and *Phragmites* marsh, respectively. Across samples, soil organic C to N ratios ranged from 6.8 to 23.4 (10^{th} to 90^{th} percentiles) and values were greater in samples dominated by emergent marsh compared to aquatic vegetation or algal mat plant communities.

In contrast, Soil P was not correlated with SOC, total C, or inorganic C concentrations (r^2 < 0.12), suggesting that the mechanisms that control N and P accumulation in these wetland soils differ. Instead, Soil P and HCO_3—extractable Olsen-P were highly correlated (r^2 = 0.76). It is not clear whether, or to what extent, Olsen-P is associated with loosely-bound and more redox-sensitive Fe/Mn fractions of these wetland soils. It may be that the Olsen-P fraction represents P adsorbed from the water column, and this labile P is gradually incorporated into more recalcitrant P fractions over time. Alternatively, Olsen-P may simply represent a small fraction of soil total P that is controlled by soil parent materials or other geological factors. A recent project investigating soil-P fractions from a series of nearby impounded wetlands reported similar soil total P concentrations as for fringe wetlands, and found that the largest pool was in the Ca-bound fraction (74%; Teeters, 2015). Loosely-sorbed and Fe-bound P fractions accounted for 80 to over 200 mg P/kg, slightly larger than Olsen-P concentrations for fringe wetland soils (Table 18), and were associated with elevated rates of P sediment flux. Since >90% of soil samples had pH > 7.35, and previous work in similar wetland soils showed a strong correlation between total C and Ca concentrations (r^2 = 0.79; DWQ, 2015; [*Willard Spur*]), wide soil C to P ratios ranging from 42 to over 200:1 (10^{th} to 90^{th} percentiles) suggest that fringe wetland soils may serve as effective long-term sinks for available P.

4.4.1.2 Soil trace elements

The abundance of trace elements in wetland soils reflect a variety of sources and processes, from geologic substrates liberated by soil forming processes to historical and contemporary loads driven by human-induced disturbance (e.g. mining and mineral processing, industrial discharges, roads, and agricultural use (soil erosion, irrigation return)). Distributions of concentrations for 14 trace element from surface soils (0-10 cm) of fringe wetlands is described in Table 18, based on transect averages. Transect averages were found to exceed benchmarks for five elements: As, Ba, Cd, Pb and Zn based on Probable Effects Levels (PELs; except as noted in Table 18), derived from NOAA's '*Screening Quick Reference Tables*' (SQuiRTs; *Link*)(Table 18). The distribution of site x transect averages for the metals shown in Table 18, among dominant water sources, are provided in the Appendix (see: Figure 31, Figure 32, and Figure 33). Of particular note are the relatively large number of exceedances for Ba (32 site x transect samples) and Pb (10 site x transect samples). Figure 33 shows that Ba concentrations in GSL fringe wetland soils are typically greater than the 67 mg/kg background, and that soil Ba concentrations are not strongly related to the dominant water sources to these wetlands. This figure also shows the distribution of soil Pb concentrations, by dominant water source, where most of the exceedances were found in soils receiving treated effluent from UPDES facilities and soils within the Jordan River delta in Farmington Bay. These elements are commonly associated with industrial, and to a lesser extent agricultural sources, while a substantial amount of lead (Pb) deposition may be associated with historical (and presently discontinued) smelting practices and the use of alkyl-Pb additives in automobile fuels (Alloway, 2012; DWQ, 2015). Trace elements in soils occur as a wide array of chemical species (e.g. as carbonates or sulfides) and many are strongly

Table 18. Summary Characteristics of Wetland Soil Trace Element and Extractable Nutrient Concentrations

Parameter	Units	Num. of Obs	Percentiles *			Range	Background Level **	Benchmark (PEL) **	# Transects Exceeding §	Comments
			25th	Median	75th					
Trace Elements										
Aluminum (Al)	mg Al/kg	84	1698	2115	3038	4812	2,600	18,000	0	
Arsenic (As)	mg As/kg	84	2.40	4.97	8.87	18.6	1.1	17.0	2	Associated with agricultural and industrial sources
Barium (Ba)	mg Ba/kg	84	99	116	141	187	67 ‡	130	30	See Note [1] for benchmark; Industrial sources
Cadmium (Cd)	mg Cd/kg	84	0.28	0.35	0.79	3.89	0.2	3.5	2	See Note [2] for benchmark; Agricultural sources
Cobalt (Co)	mg Co/kg	29	1.88	2.43	3.44	3.93	1.85 †	10	0	See Note [3] for benchmark; Industrial sources
Chromium (Cr)	mg Cr/kg	51	3.08	3.79	5.79	7.87	10 **	37.3	0	See Note [1] for benchmark;
Copper (Cu)	mg Cu/kg	84	6.01	11.48	35.9	62.4	25	197	0	Associated with agriculture, industry, and road sources
Iron (Fe)	mg Fe/kg	84	2580	3740	4878	8990	2,950 †	40,000	0	See Note [4] for benchmark
Manganese (Mn)	mg Mn/kg	84	222	334	415	598	400	1,100	0	See Note [4] for benchmark
Nickel (Ni)	mg Ni/kg	84	4.44	5.77	7.22	15.9	9.9	36	0	Associated with agricultural and industrial sources
Lead (Pb)	mg Pb/kg	84	10.5	16.2	49.4	119.8	10.5	91.3	10	Associated with roads and industrial sources
Selenium (Se)	mg Se/kg	84	0.07	0.10	0.12	0.40	0.29	1.0	0	See Note [3] for benchmark
Mercury, total (THg)	µg THg/kg	84	23.8	48.0	138.5	460.2	27.5	486	0	See Note [5] for benchmark
Zinc (Zn)	mg Zn/kg	84	24.7	43.7	97.4	500.4	22.5	315	1	See Note [6] for benchmark; Associated with agriculture and industrial sources
Extractable Nutrients										
Total Inorganic N ***	mg N/kg	84	3.85	11.70	49.1	186.1				
Olsen-P	mg P/kg	84	6.83	21.6	51.2	187.0				
Extractable $SO_4^{=}$	mg S/kg	29	199.3	294.5	492.2	1391.1				
Specific Conductance	mS/cm	84	2.18	3.82	6.97	34.2				

* Percentiles calculated from all sample data for this wetland type (n=78 measurements).

** Based on values from SQuiRT tables, unless specified otherwise.

*** Extractable NH_4^+ and NO_3^- concentrations are expressed as Total Inorganic N, because of uncertainty in sample handling (freezer failure and extended time-period of sample processing) for at least five fringe wetland sites.

§ Based on number of transects (n=84), average of sample measurements across each transect.

‡ Background value from Alberta Environment (2009). † Background levels estimated from Johnson et al. (2012)

[1] Toxic effects level (TEL) from NOAA's Screening Quick Reference Table (SQuiRT) for marine sediments.

[2] Value for freshwater sediments given, marine sediment value is 4.2 mg/kg.

[3] Apparent effects threshold (AET) for marine sediments.

[4] Severe effects level (SEL) from SQuiRT tables.

[5] Value for freshwater sediments given, marine sediment value is 700 mg/kg.

[6] Value for freshwater sediments given, marine sediment value is 271 mg/kg.

sorbed to clay mineral or Fe/Mn-oxide surfaces. As such, bioavailability to sensitive organisms is expected to be lowest in soils, compared to surface waters, particularly since $CO_3^{=}$ and HS^{-} ligands are often abundant, particularly in GSL fringe wetlands.

4.4.2 Leaf C:N and $\delta^{15}N$ signatures of Dominant Vegetation

Leaf samples from dominant plant species along each transect were collected and analyzed for C , N and P concentrations and $\delta^{15}N$ isotope ratios. The objective was to begin development of a database for plant nutrition and fertility indicators of important wetland species. Samples from 10 dominant species were collected from 86 locations in fringe wetlands in 2013. Data for the most common species (*Phragmites australis*, *Schoenoplectus americanus* [*Scirpus*], and *Distichlis spicata* were kept separate, both species of *Typha* were combined, aquatic plants (*Stuckenia sp.*) was kept distinct, and all other species with less than 4 samples (e.g. *Salicornia*, *Tamarix*, *Cardaria*, *Atriplex*) were aggregated. Indicators of plant nutrition, such as C:N and C:P ratios, are known to vary among species and ecosystem type as well as in response to soil nutrient availability. In general, higher (or wider) C:nutrient ratios suggest that that nutrient is relatively more limiting to plant growth than a lower C:nutrient ratio. In a similar vein, narrow N:P ratios suggest relatively greater P over N availability, while wide N:P ratios are more indicative of P limitations to growth.

Preliminary results are shown for leaf C:N (Figure 21), C:P (Figure 34), N:P, (Figure 22) and $\delta^{15}N$ (Figure 23) ratios among species and dominant water sources. Leaf C:N ratios are narrow and similar among species in fringe wetlands

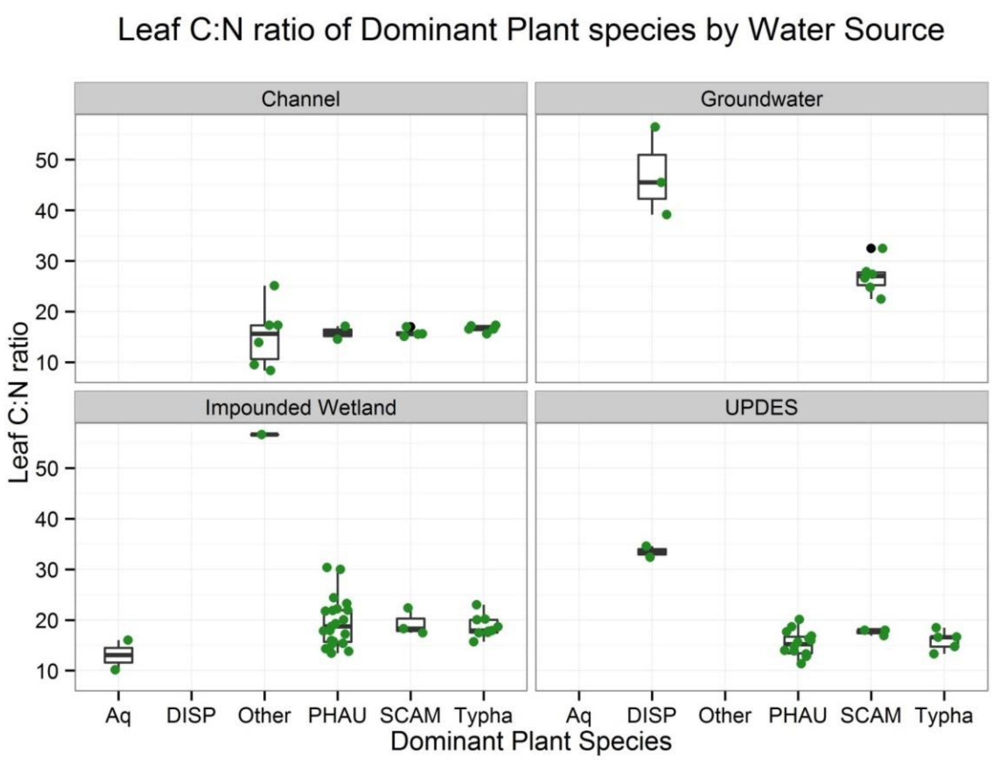

Figure 21. Leaf C:N ratio of dominant plant species, by water source.

downstream of channels and impounded wetlands, particularly in comparison wetlands with groundwater inflows. Plants in groundwater-fed wetlands (*Distchlis* and S. *americanus*) have wider C:N ratios than the same species downstream of waste water treatment plants, consistent with the idea that nutrient availability is much greater in sites receiving treated wastewater effluent.

There is relatively greater variation in leaf C:P vs. C:N ratios among species and dominant water sources. The widest ranges among species are observed in sites downstream of impounded wetlands and wastewater treatment sites (Figure 34). For example, median species C:P values range from approximately 400:1 to 200:1 for aquatic species and *S. americanus*, respectively. Similarly, *Distchlis* has a C:P >600:1 and *Phragmites* near 200:1. The C:P of *Phragmites* appears to be lowest in sites associated with channels compared to sites below UPDES discharges or impounded wetlands. At a coarse scale, apparent differences in leaf N:P ratios are subtle (Figure 22), but appear to be more narrow (higher P availability) in UPDES sites compared to sites below impounded wetlands.

Finally, leaf $\delta^{15}N$ ratios can provide information about the relative importance of various N sources that are available for plant uptake. In Figure 23, plant $\delta^{15}N$ ratios are greater in sites receiving UPDES discharge relative to wetlands with other dominant water sources. This is most likely a consequence of the high degree of organic matter processing that occurs within modern waste water treatment facilities, where large portions of the N inputs to the waste stream are lost as gaseous products resulting from chemical and biological processes; these processes also happen to result in isotopic fractionation which produces the enriched $\delta^{15}N$ signal of the remaining material.

We also see evidence that leaf $\delta^{15}N$ ratios may vary with distance from the water inflows, at least in some system types (*data not shown*). However, three of the four samples missing from the dataset are from the 100-m distance, from one site, that had the highest $\delta^{15}N$ signatures (Central Davis 01), such that the apparent increase in $\delta^{15}N$ could be due to a sample completeness issue. Figure 35 shows how differences in leaf $\delta^{15}N$ ratios between impounded wetland and UPDES water sources varied with distance along the wetland flowpath, for a single plant species

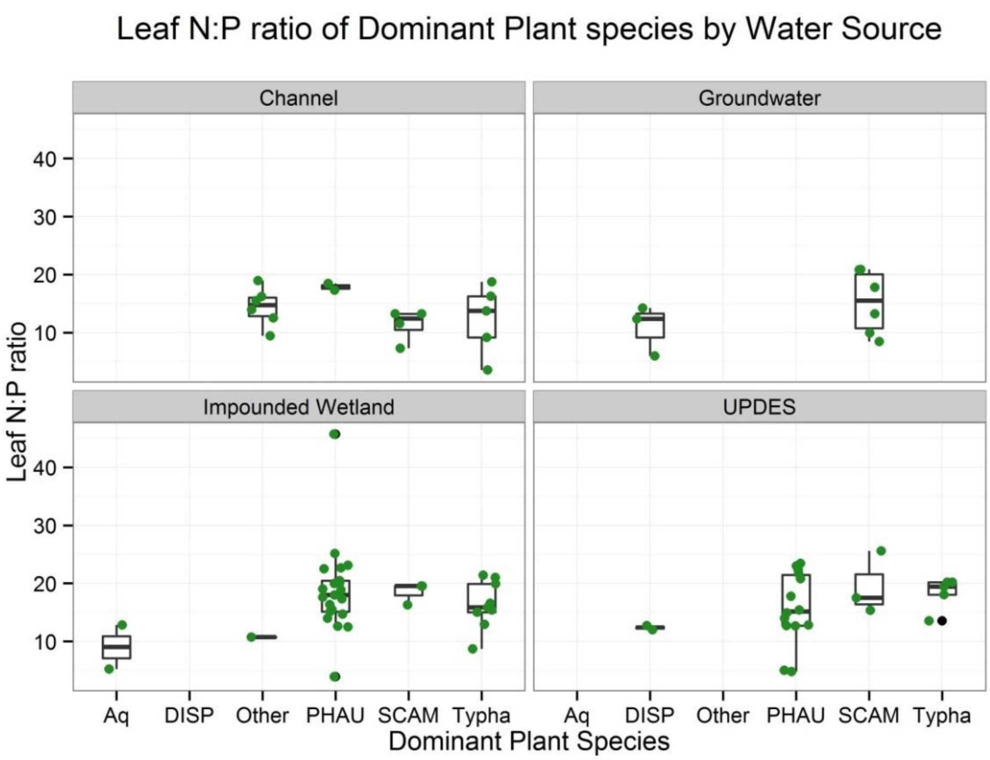

Figure 22. Leaf N:P ratio of dominant plant species, by water source.

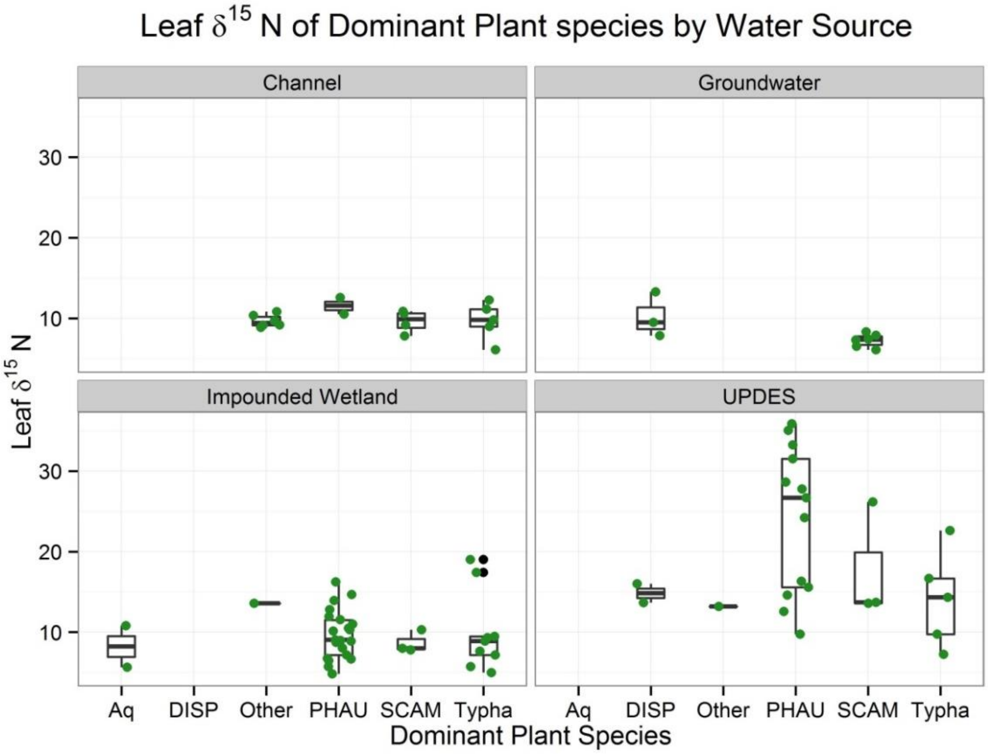

Figure 23. Leaf δ^{15}N isotope ratio for dominant plant species, by water source.

(*Phragmites australis*). Leaf δ^{15}N ratios were close to 30 ‰ in UPDES wetlands (Figure 35), a considerable enrichment compared to values near 10 ‰ for sites below impounded wetlands. Interestingly, while leaf δ^{15}N ratios were quite distinct between impounded wetland and UPDES water sources at 500 m from the inflow(Figure 35), leaf C:N ratios were very similar (Figure 36). This suggests that while the WWTP signal, as leaf δ^{15}N ratios, persists up to 500 m into these wastewater-dominated fringe wetlands, the effect of treated wastewater effluent on nutrient availability to emergent vegetation, as leaf C:N ratios, was attenuated at distances between 300 and 500 m from the inflow for the three fringe wetlands below UPDES facilities examined here.

4.5 Chemical Characteristics of Dominant Water Sources to Fringe Wetlands

Previous work on GSL fringe wetlands highlighted various water sources as an important way to evaluate differences in the structure and biological (taxonomic) composition among sites (DWQ, 2015b). Distinct water source classes were useful in describing variation in plant and benthic macroinvertebrate community composition as well as water chemistry data. We continued this approach in the current report (see Section 2.2.2 and Table 6), and found that different water sources were more important in explaining among-site differences in biological response and water / soil chemical data than HUC8 watersheds.

Given the large number and variety of variables measured in this study, and the complexity in how these variables interact within and among aquatic bed to emergent wetland habitats, we explored which aspects of upstream water sources to fringe wetlands are the most important drivers affecting ecosystem type as well as relative health (i.e. condition). An initial effort applied NMDS to upstream chemistry and site variables, but the ordination results were simply too complicated to interpret (at least 4 dimensions were needed, given the large number of variables). Instead, we used Random Forest (RF) models (classification mode) to identify which water and soil chemical variables were most important in discriminating among the five water source classes: *Channels*, *Groundwater*, *Interior* areas of large GSL bays, *Impounded Wetlands*, and *UPDES* wastewater treatment plants. A limited series of RFs were used to sort out the most important variables based on whole-model out of bag error rates (OOBERs) and the global 'Mean Decrease in Accuracy' (MDA). Because autocorrelation among variables can lead to problems interpreting RF models, groups of variables (e.g. water nutrients versus major ions) were identified with high MDA values and the 'selective harvest' RF models were re-run.

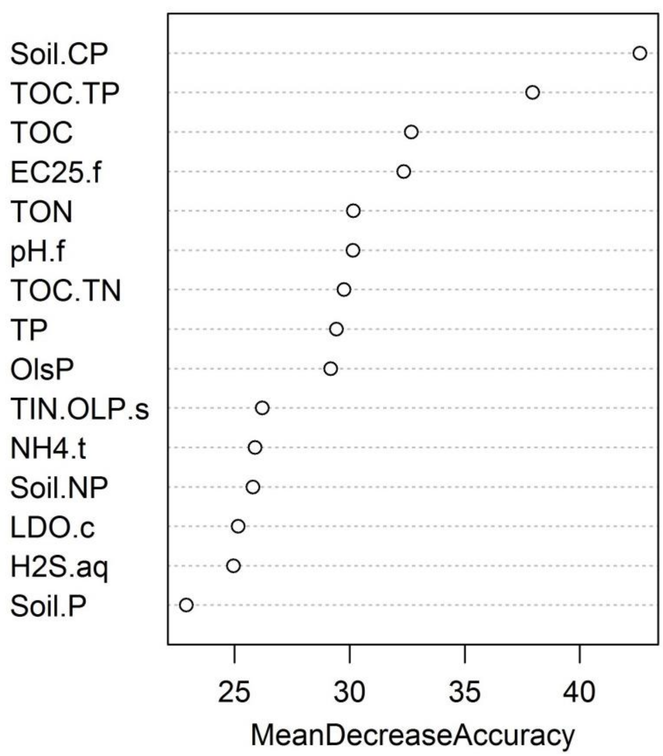

Figure 24. Random Forest Variable Importance Plot for Fringe Wetland Water Sources: Water and Soil Nutrients

Water and soil chemical variables were identified early on as important variable groups, with 73 variables in the initial model (see Table 17 for parameter groupings). Subsequent thinning identified 15 variables from three key variable classes (out of 48 variables) with highest MDAs (Figure 24) and resulted in OOBERs of 8.3 to 11%: water column nutrients, water column metabolism, and soil nutrients. Interestingly, the model with only 15 variables had an OOBER of 10.7%, indicating no apparent reduction in prediction ability compared to the larger dataset.

The following three figures illustrate differences in key water and soil chemistry variables among the five water sources upstream of fringe wetlands (variables are shown in order of decreasing global MDA). Key differences in water column nutrients among water sources are shown in Figure 25. Based on the class-specific MDAs derived from the 15-variable RF model (*data not shown*), TOC:TP ratio is powerful in correctly separating out UPDES and Channel sites; both TOC and TON identify GW and Interior sites; and TOC:TN, TP, and NH_4^+ identify UPDES sites.

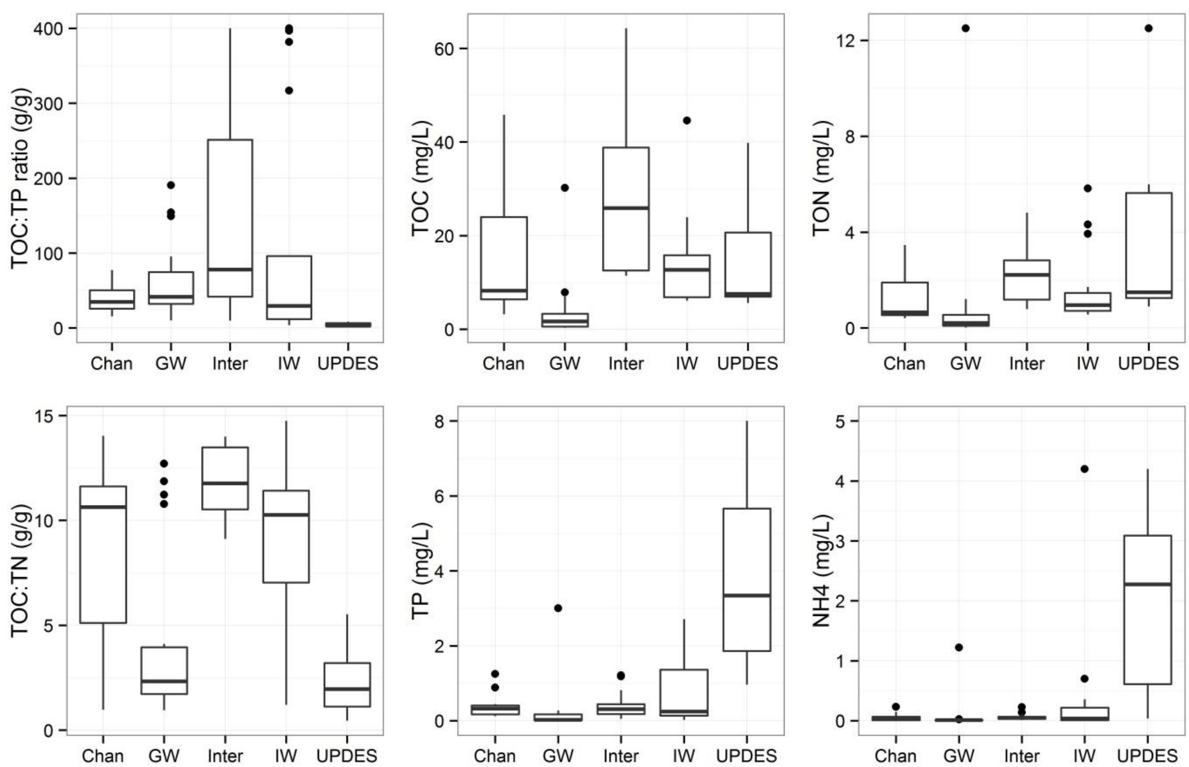

Figure 25. Key differences among Water Sources: Water Column Nutrients

Similar comparisons can be made for water column metabolism (Figure 26) and soil nutrients (Figure 27). A few interesting differences include higher water pH values in Interior wetland sites, particularly compared to sites below GW and UPDES sources; and lower DO concentrations in sites below IWs and UPDES sources (Figure 26). For soil variables, the Total C:P ratio was the single most important variable in the RF model (had the greatest global MDA) and was important in distinguishing Interior and Channel sites.

While useful as a classification model, the RF analysis was also quite useful as a variable reduction tool. In terms of nutrients, it is interesting that C:P ratios of the water column and surface soils described important differences among water sources. Along these same lines, there are strong similarities between water column TP and soil Olsen-P and Total P concentrations. Further work will be needed to clarify the magnitude and direction of interactions between water column and soil (available) P.

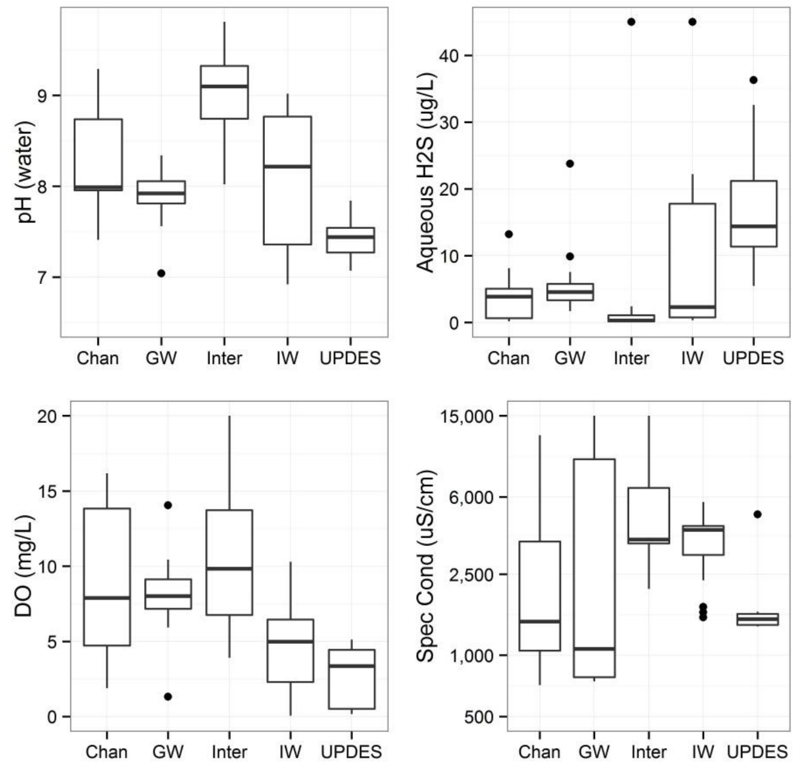

Figure 26. Key differences among Water Sources: Water Column Metabolism

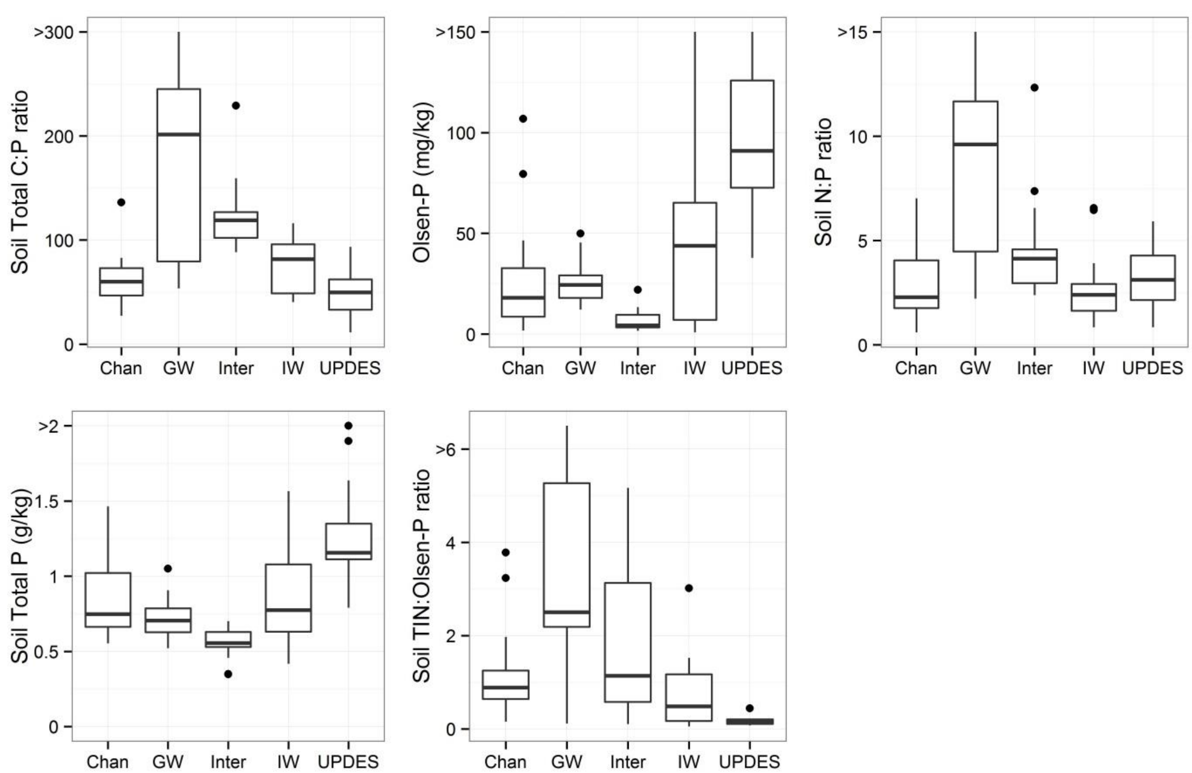

Figure 27. Key differences among Water Sources: Soil Nutrients

4.6 Fringe Wetland Biological Stressor-Response Models

A central goal of this project was to develop techniques to characterize (and ultimately assess) 'good' versus 'poor' ecological conditions of GSL wetlands in response to a range of stressors that affect these systems. We built upon previous work identifying preliminary biological response metrics for GSL wetlands, and used the Random Forest modeling approach (described in the previous section of this report) to identify important suites of variables that affect biological response measures, and propose benchmarks or breakpoints between classes of biological response (as appropriate).

4.6.1 Chlorophyll-a

Chlorophyll-a concentrations varied widely in surface waters of fringe wetlands. Concentrations ranged from 2 to over 50 µg/L, although > 50% of samples were below analytical reporting levels (Table 17). While highest chlorophyll-a levels were found in waters with highest total nutrient concentrations, which is expected since phytoplankton would be included in measurements of total (unfiltered) nutrient concentrations, it is not clear what over variables might also be important drivers within this ecosystem type.

The initial RF model included 64 variables (water column nutrients, major ions and indicators of aquatic metabolism; site characteristics; and soil nutrients), and accounted for 29.5% of total variance, with mean square of residuals (MSE) of 1015. A reduced model (32 variables) was similar to the initial model (25% variance explained and MSE = 1080). The relative of importance of the top 15 variables is shown in Figure 28. As expected, total nutrients (and TP and TN:TP ratios) were important predictors of chlorophyll-a, but salinity (as specific conductance, and Na^+ and Cl^- concentrations) were also important (% increase in MSE (after dropping a variable) was > 10%), with increasing chlorophyll-a as salinity increased (up to 10,000 µS/cm). Importantly, removal of TP and TN:TP ratio variables severely degraded the model, to ~ 12% of variance explained (MSE ~ 1257). This is likely as good a model as possible for this ecosystem type, given the limited amount of data above analytical reporting levels. However, other aspects of plant productivity may be more important for fringe wetlands.

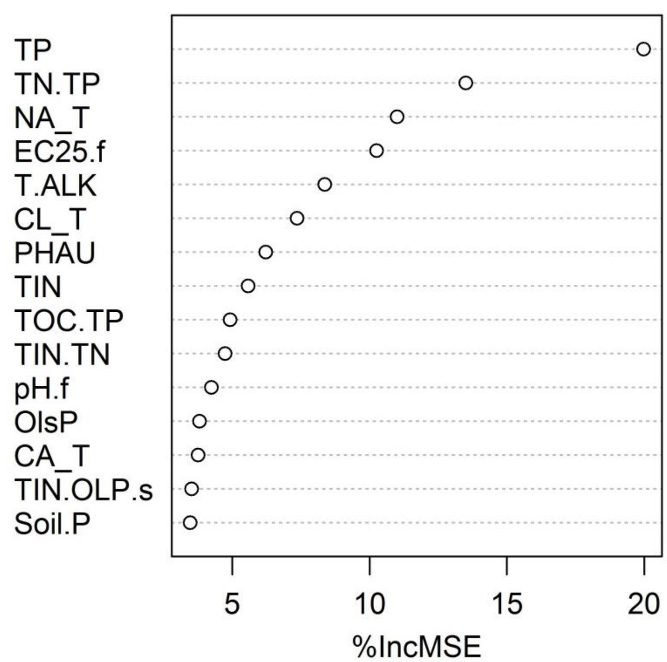

Figure 28. Variable Importance Plot for Chlorophyll-a concentrations

4.6.2 Water Column pH (and exceedance values)

Water column pH is a key feature of aquatic metabolism and a standard water quality parameters used to protect aquatic life. In fringe wetlands, over 15% of samples exceeded the 9.0 numeric criterion for aquatic life (75th percentile is 8.78) and values can reach 9.5 or more. In other GSL wetland systems, high pH appears to be related to high rates of photosynthesis within the water column, attributed to either phytoplankton or SAV (DWQ, 2015d).

The initial model included 52 variables describing water column nutrients, major ions and indicators of aquatic metabolism; site characteristics; and soil nutrients, explained 72% of total variance and had MSE of 0.14. A thinned model of the best 15 variables explained 75% of variance (MSE of 0.13) (Figure 29). Dissolved oxygen was an important predictor of water column pH; this is unsurprising since increases in DO reflect increasing net photosynthesis and a decrease in dissolved CO_2 and/or HCO_3^- concentrations, which drives pH upward. Interestingly, two measures of soil P availability (Olsen-P and the Olsen-P to Total P ratio) and water column NH_4^+ concentrations were inversely related to pH, however, the significance of these interactions is unclear.

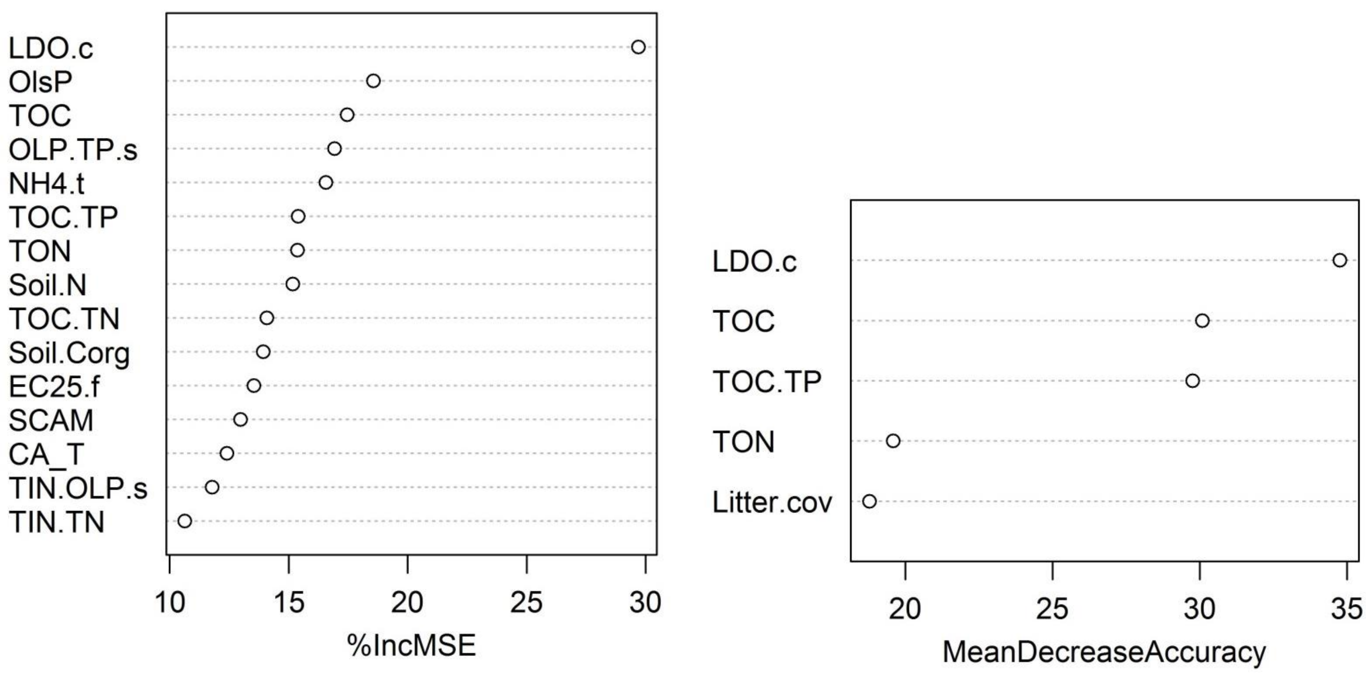

Figure 29. Variable Importance Plot for Water Column pH (left) and pH-Exceedance (right)

Since we were also interested in identifying potential drivers that could explain exceedances in water column pH, an RF model was re-run as a classification problem, with pH reclassified as ≥ 9.0 ('yes') or < 9.0 ('no'). The pH-classification model was readily trimmed down to five important variables with an OOBER of 3.6% and misclassification rates of 1.4% ('Not exceeding' 1/68) and 13.3% ('Exceeding' 2/13). Similar to the above RF-regression model, DO, TOC, TOC:TP ratio, and TON concentrations were positively associated with pH exceedances, while the cover of raised surface litter (Litter.cov) negatively associated with pH exceedance. This simple model provides an 'Exceedance' error rate of 13.3% based on misclassifying 2 of 15 samples, and is consistent with the 'regression mode' RF model results.

4.6.3 NH_3 Toxicity (and exceedances values)

NH_3 toxicity in stagnant waters can be an important consideration for water quality efforts, particularly for wetlands that received nutrient-enriched waters from agricultural and urban watersheds. As described in Table 17, we observed exceedances to NH_3 (undissociated NH_4^+) based on chronic numeric criteria for aquatic life uses that are currently in place for Utah waters. Unfortunately, there is little confidence in RF modeling of NH_3 exceedance probability due to a very limited dataset (6 exceedances out of 102 fringe wetland samples), so these calculations were not attempted for this report. Continued monitoring of GSL wetlands will, over time, provide an opportunity to explore the importance of various drivers affecting wetland N cycling and the conditions conducive to NH_3 toxicity.

4.6.4 Plant Biovolume

We modeled the drivers affecting plant dominance, estimated as biovolume (total vegetation cover x height of dominant plants), to get a sense of which aspects of water and soil chemistry were most important in limiting aboveground biomass growth. After removing plant cover data, the full model of 49 variables accounted for approximately 51% of total variance in plant biovolume. This statistic improved somewhat after removing the relative cover of invasive species (dominated by *Phragmites* cover) and thinning the model to the top 15 variables. Figure 30 clearly shows the importance of soil P availability on plant biomass (as biovolume). In addition, the cover of surface litter was an important predictor for plant biovolume and a key element of dense stands of emergent marsh. The cover of aquatic habitats (as Sum.Aq an SAV cover) was inversely related to biovolume, as was water column $SO_4^{=}$ and DO concentrations. Interestingly, the specific conductance of water – but not of soil – was an important predictor of biovolume in this model, though the magnitude of this effect, from RF partial importance plots, was small. While data at high soil salinities was limited, it appears that growth of tall emergent plants (with large biovolumes) was limited at specific conductivities above 15 mS/cm.

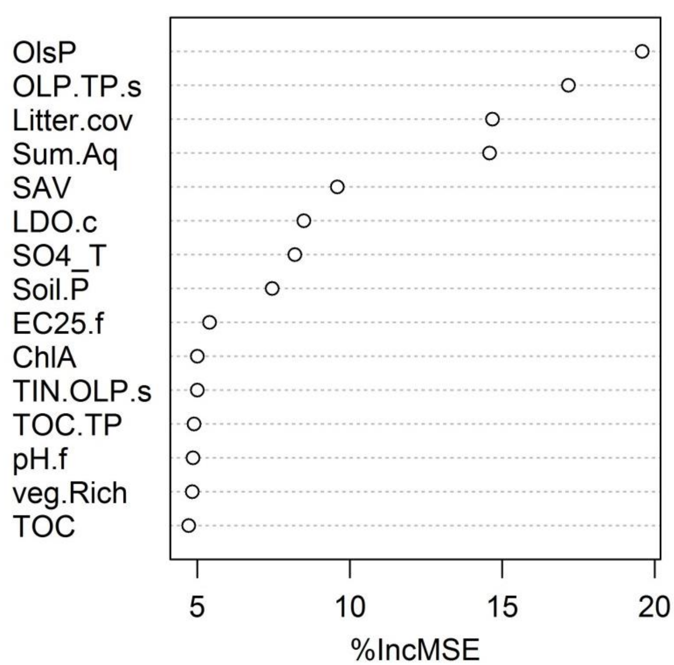

Figure 30. Variable Importance Plot for Plant Biovolume

5.0 Discussion

5.1 Preliminary metrics of interest

A modest list of potential indicators describing key aquatic and emergent features of GSL fringe wetlands were evaluated from a wide range of biological and chemical measurements at 28 sites. Given the large number of possible variable combinations and the limited number of independent sites, efficient yet productive data reduction strategies continue to be improved. Based on the work described in this report, metrics of ecological integrity (*condition*) or biological response to stress that appear promising include:

- Vegetation-based metrics include cover of *Phragmites* (relative and total), relative cover of all invasive species, and plant biovolume
- Macroinverterate-based metrics include the relative dominance of Chironomids, particularly subfamily Chironominae (tribes Chironomini and Tanytarsini), and measures of invertebrate diversity
- Water chemistry-based metrics include the number of 'exceedances' of freshwater stream aquatic life use benchmarks, some integrative measure of aquatic metabolism (based on DO, pH, chlorophyll-a, etc.), or possibly a set of multi-metric indices for water column nutrients and soluble metals. The latter index could be based on an effects ratio of sample concentration vs. appropriate benchmarks

An important data gap that can be improved by a more integrated evaluation of site conditions, perhaps by incorporating elements from Utah Geological Survey's Utah Rapid Assessment Protocol (*unpublished*), is the development of consistent and sensitive (i.e. responsive) measures that describe the relative abundance of aquatic versus emergent wetland habitats at a given site and adjacent to water chemistry and macroinvertebrate sampling locations within a wetland site. Similarly, additional elements of site and landscape-scale stress from UGS' rapid assessment would be help integrating chemical and biological stressors.

5.2 Lessons learned and next steps

A wide range of lessons were learned during both the 2013 and 2015 field seasons.

i) The hydrology of this wetland type is extremely variable in both time and space. After several years of drought and aggressive invasive species-related water management, extensive areas of emergent marsh lacked surface water – except for sites below nearby wastewater treatment plants. This limitation was reduced in 2015 by having greater field experience with this wetland type and by sampling fringe wetlands that occur within the larger brackish bays of GSL
ii) Obtaining a sufficient abundance of macroinvertebrates to support estimates of taxonomic diversity can be improved by collecting more sweeps in inundated microsites/habitats that are hydrologically integrated with the site; this effort greatly improved in 2015 vs. 2013
iii) Sample collection efforts can be further improved by working with state agency and land management personnel to access remote areas of GSL.
iv) Identification, collection and analysis of data from potential reference standard sites, that lack significant urban, industrial and agricultural stresses, should improve our ability to detect biological response (signals) from the wide range of covariates and confounding factors (noise). In 2015, we collected data from three groundwater-fed marshes in Snake Valley, a remote area of Utah's West Desert, however, it will be important to examine similar low-disturbance areas with difference wetland plant communities, particularly alkali bulrush hemi-marsh and aquatic bed habitats

v) Classification and characterization of dominant water sources to fringe wetlands appears to be a fruitful way to summarize site-scale data. Integration of site-specific variables with larger scale measures of stress may provide an excellent framework for continued monitoring and assessment of GSL wetlands

Important next steps to advance wetland sampling and data analysis procedures for fringe wetlands include:

i) Data from additional GSL-marsh sites, collected by other researchers, could be compiled and examined for useful biological response or stressor metrics and possible inclusion in the fringe wetland dataset. These data may also help in validating ecological condition models, however, minimum data requirements and measurement consistency will need to be evaluated
ii) Multivariate analysis using the Random Forest approach to classification and regression modeling can be an important step in data reduction efforts, but also for examining complex stressor-response models in wetlands
iii) A field-based classification of key wetland types is needed, based on plant community composition and/or site structural features (e.g. abundance of aquatic bed and emergent wetland habitats), in order to develop a consistent set of ecosystem types. Because hydrologic conditions can vary so widely within GSL wetlands, it is important to identify appropriate classes of features that can be compared along environmental and stressor gradients

Next steps for fringe wetland assessment include continued field sampling from a wider range of sites, development of data analysis techniques that integrate reference standard and disturbance gradient data into an assessment framework, and comparison of current results with historical data. In addition, DWQ will begin in-depth facilitated discussions with stakeholders on establishing water quality goals for Utah's wetlands, including designated uses and key ecological attributes for major wetland classes associated with Great Salt Lake.

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7.0 Appendix -- Additional figures to accompany text

7.1 Soil Metal Concentrations among Water Sources

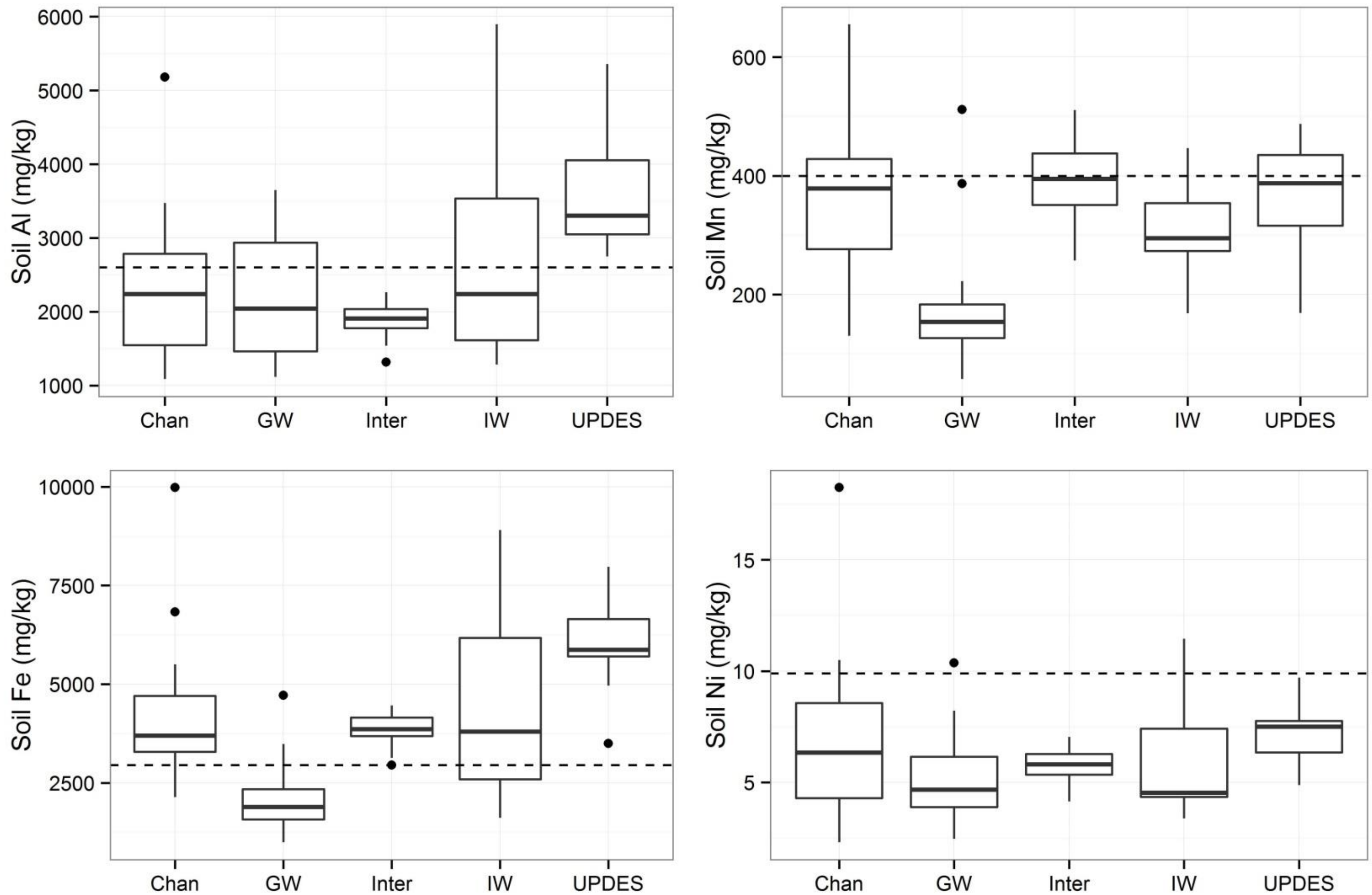

Figure 31. Soil Metal Concentrations by Dominant Water Source (Al, Mn, Fe, and Ni).

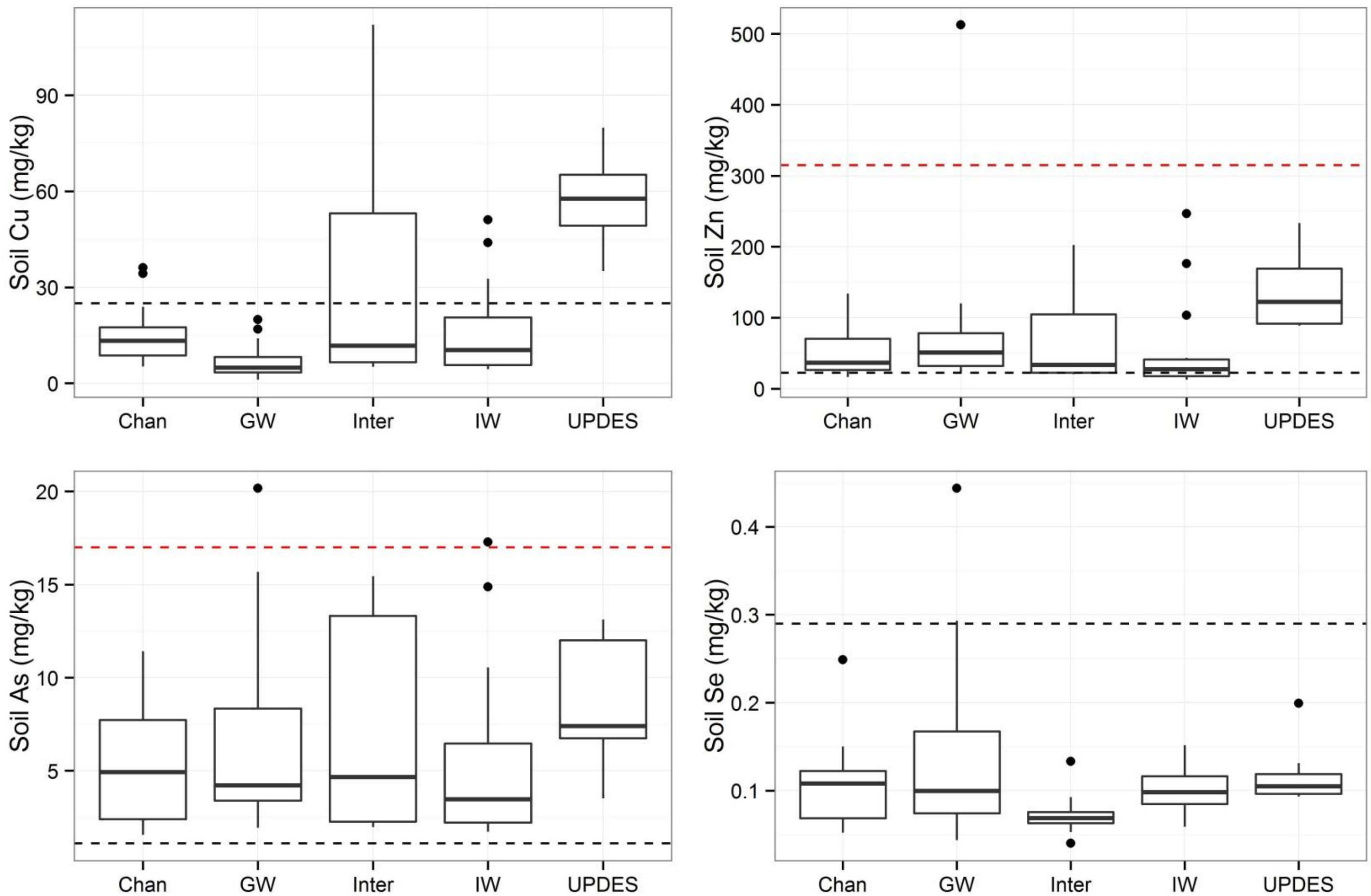

Figure 32. Soil Metal Concentrations by Dominant Water Source (Cu, Zn, As, Se).

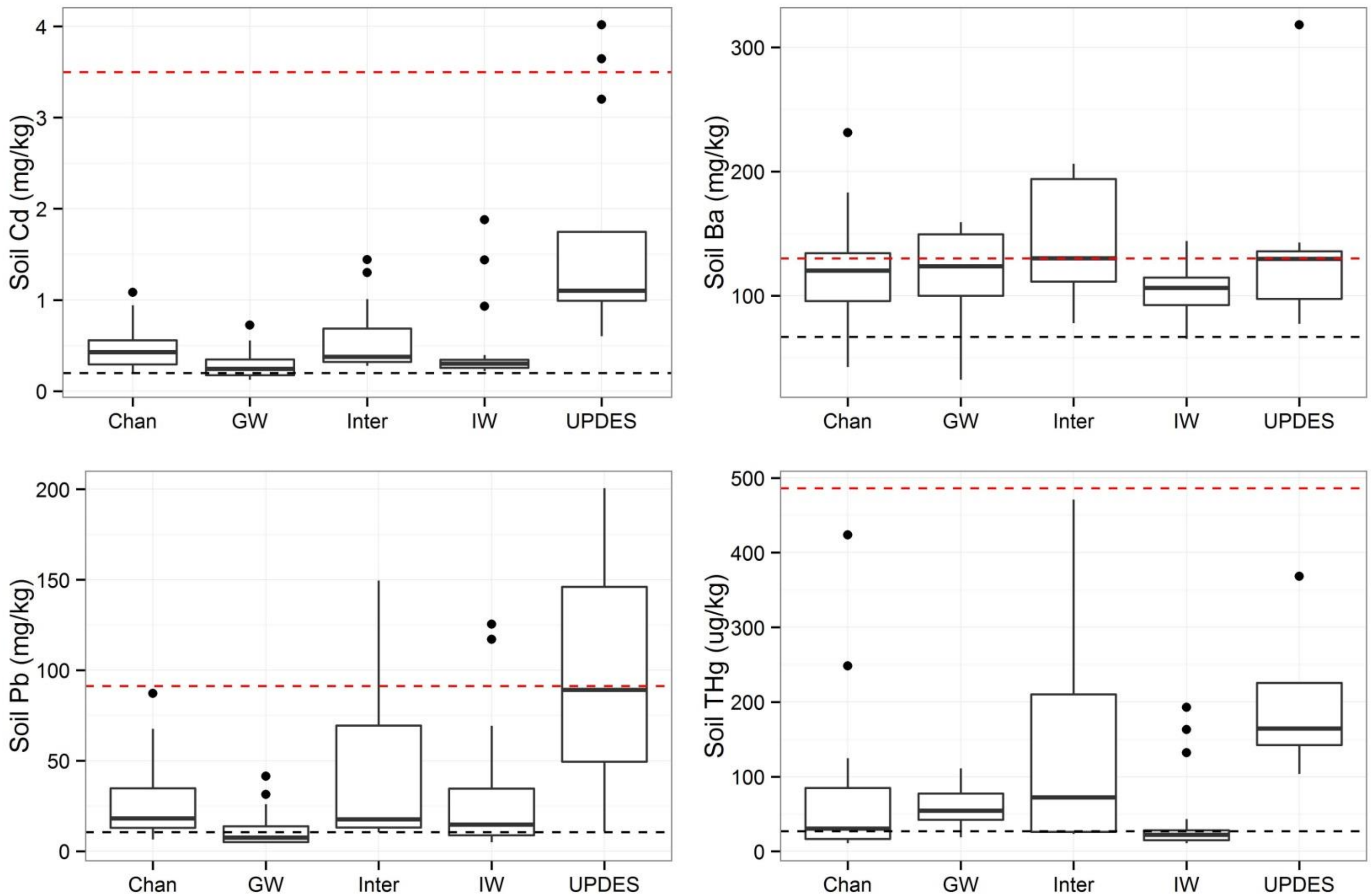

Figure 33. Soil Metal Concentrations by Dominant Water Source (Cd, Ba, Pb, and THg).

7.2 Leaf Nutrient Patters by Water Source

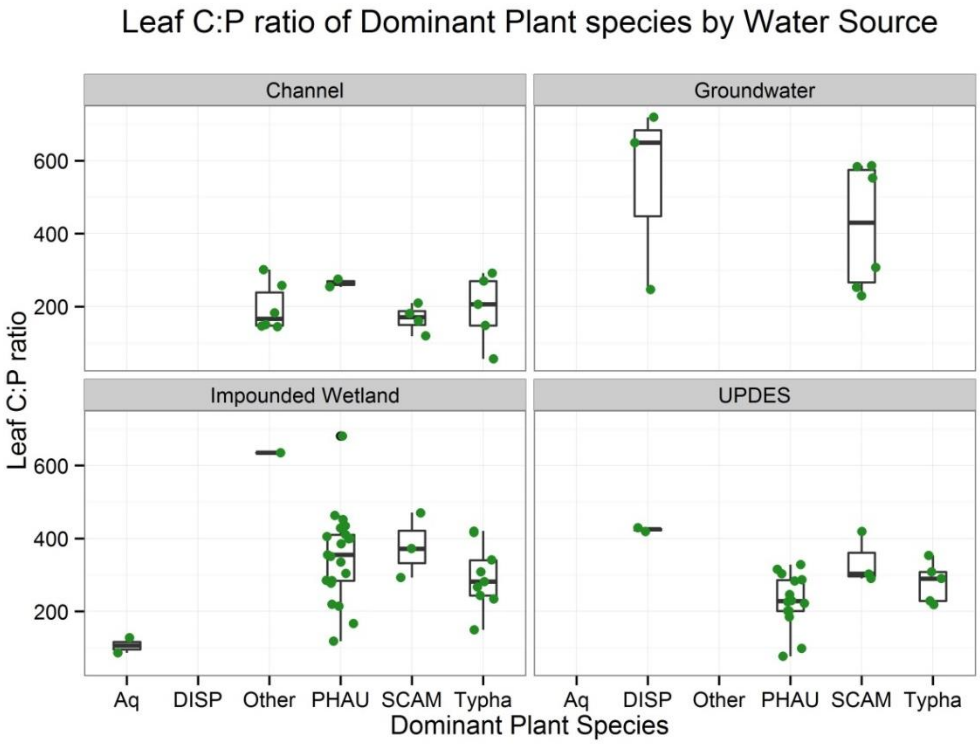

Figure 34. Leaf C:P ratio of dominant plant species, by water source

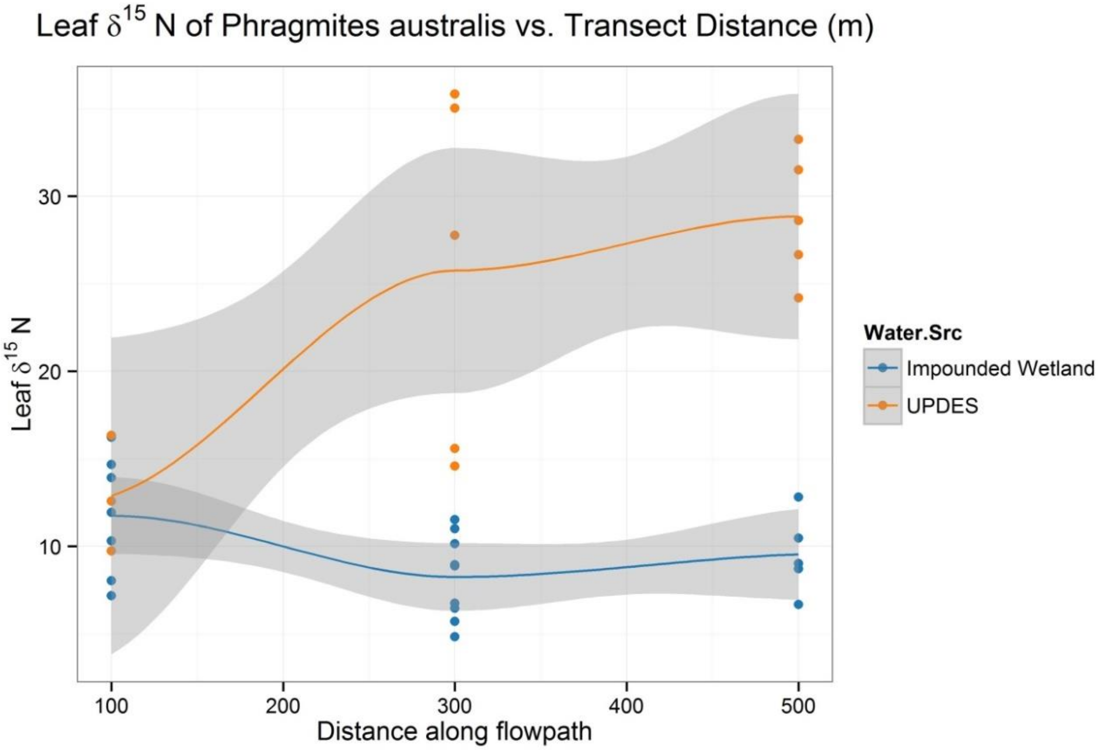

Figure 35. Leaf δ^{15}N signatures of *Phragmites australis* vs. distance from water inflow.

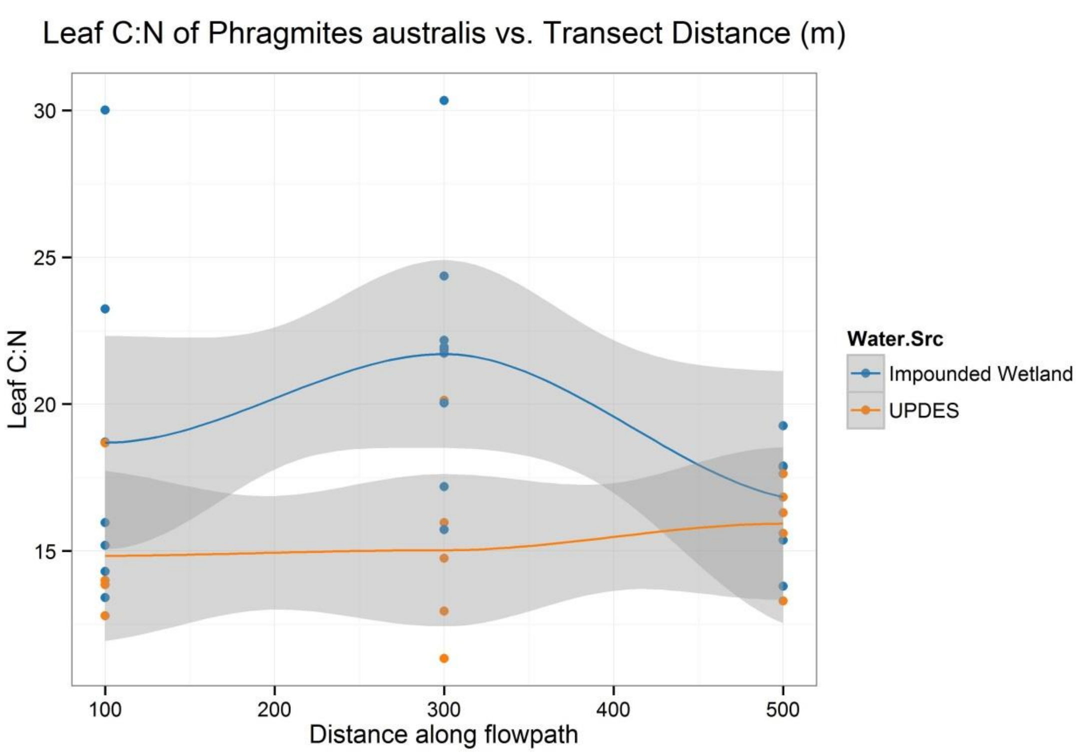

Figure 36. Leaf C:N ratios of *Phragmites australis* vs. distance from water inflow.