SUBALPINE WETLANDS: CHARACTERIZATION, ENVIRONMENTAL DRIVERS, AND RESPONSE TO HUMAN PERTURBATION AND RESTORATION

by

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the Division of Graduate Education.

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Sunni Marie Heikes-Knapton

May 2009

DEDICATION

To Duncan- for your absolutely endless supply of support, encouragement, understanding, friendship and conversation. Being your student has been one of my life's greatest experiences.

To Otto Stein and Brian McGlynn- for providing crucial assistance in ensuring that this research was rigorous and valid in the broader eyes of science.

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To Maida and Finley- for helping me to remember that "Goodnight Moon" should always be the most important publication that I read in a day.

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ABSTRACT

The subalpine region throughout the western US is increasingly pressured by land use changes. Consequences of these changes often involve major alteration to the original function of the landscape, particularly concerning wetland and riparian areas. In southwest Montana, large developments have recently been created or expanded in the subalpine environment. Wetlands in these regions bear a particularly unique structure, and often are influenced by the effects of development. The alteration to structure can result in disturbance to the original hydrological, ecological, and biogeochemical functions of wetlands. Restoration efforts attempt to mitigate for development influences, but the monitoring and success criteria do not wholly address the functional attributes of these features. At the same time, little is known about the structure of undisturbed subalpine wetlands and how environmental drivers influence the undisturbed structure and hydrological, ecological, and biogeochemical functions. Knowledge of these natural processes is necessary to ensure appropriate management decisions and future restoration success.

This study examines small subalpine wetlands in an elevation range of 2256-2316 m located in southwest Montana. Study sites include two wetland types, in undisturbed and restored conditions. This research examines physical, chemical, biological, and hydrological attributes of wetlands in varying conditions, to define and compare wetland characteristics, determine primary environmental drivers of wetland ecological and biogeochemical functions, and compare response to human perturbation.

Comparisons of our data indicate significant differences in all categories of parameters, and include metrics of biodiversity, primary productivity, hydrologic regime, and physical and chemical properties of the soil. Several environmental drivers are identified, with the primary driver of vegetation and redox response variables being depth to water and persistence of saturated conditions. The depressional wetland type is characterized by a distinct hydrologic regime, with these conditions being significantly related to a greater number of ecological and biogeochemical functions than the linear wetland type. Restoration data indicate that the restoration methods employed are sufficient in establishing the primary wetland characteristics used in wetland definition. However, the trajectory of restored wetlands indicates that long term recovery may result in wetlands exhibiting different structural and functional attributes than intended.

INTRODUCTION

"Development along rivers and streams that destroys protective riparian areas is possibly the single most urgent ecosystem threat facing Montana today."

Montana Governor Brian Schweitzer

“Rarely is it acknowledged that restoration is a hope, not a guarantee.”

Joy B. Zedler

Subalpine Wetland Ecosystems: Distribution, Function, Status and Threats

The subalpine region is the second highest biogeoclimatic zone, occupying a substantial area in mountainous regions around the globe. The subalpine in the physiogeographic region of the Northern Rocky Mountains has been defined as the vegetation life zone occupying elevations from 2073 m to 2743 m, with uppermost limits defined by the treeless region of the alpine. Situated in this dynamic and often harsh landscape, the subalpine region supports a diverse and often vulnerable community of flora and fauna (Windell et al. 1986, Barbour 1988, Finch 1992).

In the subalpine region, localized hydrological processes often create saturated or inundated conditions which support biologically diverse wetlands, exhibiting distinct soil, water and vegetation characteristics (Windell et al. 1986, Hansen et al. 1988, Hansen et al. 1996). Existing classification systems identify numerous wetland types found in the subalpine (Cowardin et al. 1979, Brinson 1993a). Subcategories of montane and subalpine wetlands of the Rocky Mountains have been based on vegetation type, substrate, and water type resulting in 13 wetland communities (Windell et al. 1986). Although work by Windell et al (1986) provides the most comprehensive description of the structure and function of subalpine and montane wetlands, this and many other works focus on large wetlands that occupy significant areas of the landscape. While little is known about the wetlands of the subalpine, even less is known about the small wetlands that occupy the subalpine region. Common wetland types of Montana include riverine, slope, and depressional wetlands (Hansen et al. 1996, Ellis and Richard 2003), all of which are found in the subalpine.

It is well known that wetlands occupy a small portion of the total global landscape (Mitsch and Gosselink 1993), and the subalpine is no exception. Estimates indicate that only 4% of the total landscape area of Montana is associated with riparian and wetland habitats (Redmond et al. 1998), that a majority of these are geographically isolated or ephemeral (Vance 2009), and only a fraction of the total are found in the subalpine. However, there exists no systematic inventory of wetlands in Montana, the state that occupies the greatest area of the Northern Rocky Mountains and which contains a large subalpine region (Ellis and Richard 2003).

The ecosystem services provided by global wetland communities are numerous and diverse (Mitsch and Gosselink 1993). Windell et al. (1986) lists a host of ecological values provided by montane and subalpine wetlands, including groundwater discharge/recharge, water purification, nutrient cycling, as well as primary and secondary production. Although little was known about the function of Rocky Mountain wetlands, Windell et al. (1986) assumed values of other North American wetlands could be conservatively applied.

More recent research specifically examines other ecosystem services provided by wetlands such as those found in the subalpine. Riparian areas, similar in many ways to wetlands, play a critical role in maintaining biodiversity (Naiman et al. 1993). In the western U.S., this is related to the presence of water in an otherwise arid landscape (Hansen et al. 1996, Patten 1998). Redmond et al. (1998) reported for Montana that the predicted richness of native terrestrial vertebrates for riparian land cover types was overwhelmingly higher than the predicted richness of the other 44 land cover types mapped for the state. Additionally, subalpine wetlands support a unique ecology of rare plants not found in other wetland types, and can serve a vital role in wildlife habitat functions (Comer 2003).

Montane and subalpine wetlands serve an important role in physical and chemical processes; including uptake of uranium (Owen and Otton 1995), sediment deposition and export (Arp and Cooper 2004), and as a primary influence on the nutrient content of the larger downstream drainage network (Brinson 1993b). More recently, interest has gained in recognizing subalpine wetlands as playing a role in atmospheric carbon cycling (Wickland et al. 2001, Chimner and Cooper 2003), a critical global issue on the subject of climate change.

The correct land area status of subalpine wetlands, as well as any changes to the land area status, may be particularly difficult to determine. National investigations of wetland status and trends that have recently been performed by the U.S. Fish and Wildlife

Service (FWS) (Dahl and U.S. Fish and Wildlife Service. 2005), are based on wetlands with sufficient size and exposure to be viewed in aerial imagery. Through the use of this approach, it becomes apparent that small wetlands occupying areas with a significant vegetation overstory, such as many of those found in the subalpine, will be difficult to identify on aerial imagery. Therefore, the exact area of subalpine wetland acreage, and any changes to the acreage due to disturbance, will be difficult to quantify for status and trends reports.

Further compounding the difficulties in managing the conservation of these critical resources is the historic and current patterns of anthropogenic influence on the subalpine region and wetland features. Disturbance to riparian ecosystems in the semi arid west is well documented (Patten 1998), and impacts to the subalpine from settlement and development continue today (Baron 2002). The initial processes associated with resource extraction created the most significant in-roads to the subalpine region, many of which have continued use. Recently, the subalpine region has experienced increased pressures due to land use changes associated with population influx and exurban residential development (Baron 2002, Gude et al. 2006), as well as recreational development (Godde et al. 2000) and continued and expanded resource extraction (Macyk 2000).

Anthropogenic disturbances in the subalpine region are known to negatively influence the structure and function of subalpine wetlands. Since a commonly used definition of a wetland is based on the hydrology, soils and vegetation of a site

(Laboratory 1987), research of wetland structure and function often addresses these characteristics and the differing factors that influence these variables.

The primary consequence of disturbance is often observed directly within the boundaries of subalpine wetlands, and commonly focuses on surface water quality. Kim et al (2001) examined several disturbance types in the Lake Tahoe Basin, and noted significant increases of N and P concentrations of surface waters linked to residential and agricultural activity. Additionally, this study noted links between road maintenance and conductivity of wetland surface waters, another common indicator of water quality.
Soil characteristics and processes of subalpine wetlands also are found to respond to disturbance. Sediment accumulation rates in marshes of the Lake Tahoe basin are linked to golf course construction, logging and road construction (Kim et al. 2001). Research in Summit County, Colorado, indicates that subalpine wetlands exposed to acid mine drainage have altered organic matter processing, peat accumulation and nutrient cycling (Arp et al. 1999).

Alteration of vegetation composition in subalpine wetlands is also noted to coincide with disturbance activity. Species composition is related to disturbance-altered conductivity and nutrient content of marsh water (Kim et al. 2001) as well as increased water depth linked to drought effects (Rejmankova et al. 1999). Kim et al (2001) also linked the presence of exotic species with disturbance-induced decreased water quality.

As a secondary consequence, the position of many subalpine wetlands as first order streams plays an important role in hydrology and downstream water quality, with chemical degradation often linked to direct or adjacent disturbance. Research on the hydrologic effects of mountain development in Europe indicates a decrease in water infiltration on the landscape, consequently contributing to erosion and increasing magnitude of flow during run off events (Koscielny 2008). Other research on headwater streams emphasizes this disturbance-water quality relationship, where degraded conditions result in degraded water quality (Dodds and Oakes 2008).

The structure and function of subalpine wetlands have been shown to be directly affected by the historic and continued land use changes of the region. To a large extent, conservation and management of subalpine wetlands falls under the subject of wetland regulation, which has a varied history and a performance record that brings uncertainty to the future of these features.

Wetland Regulation

In the contiguous United States, wetlands comprised an estimated area of 221 million acres prior to presettlement times. By the 1980s that number had decreased to 104 million acres, an estimated loss of 53% (Dahl and U.S. Fish and Wildlife Service. 2005). Attempts to halt and even reverse the national loss of wetlands have been, and continue to be, addressed by enforcement of the Clean Water Act and the advisement of the "No Net Loss" policy introduced during the first Bush administration.

Since the 1970s, the Federal Water Pollution Control Act (Clean Water Act - CWA) (33 U.S.C. 1344) has held an objective "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters". Under Section 404 of the CWA, discharge of dredged or fill material in wetlands is regulated primarily by the U.S.

Corps of Engineers, with joint assistance from the U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency.

The public and political awareness of wetland loss was also increased by the federally sponsored National Wetland Policy Forum. In 1988, President George H.W. Bush echoed the National Wetland Policy Forum's introduction of the "No Net Loss" policy. The policy seeks to:

> *…achieve no overall net loss of the nation's remaining wetlands base and to create and restore wetlands, where feasible, to increase the quantity and quality of the nation's wetland resource base* (National Wetland Policy Forum 1988)

The policy became a cornerstone for wetland conservation in the 1990's and has been embraced by subsequent administrations.

Due to enforcement of the mitigation mandate of the CWA and the adoption of the "No Net Loss" policy, wetland restoration and creation projects have significantly increased in the U.S. (Mitsch and Gosselink 1993). Mitigation has historically focused on techniques of species establishment rather than the functional values of the site (National Research Council 1992, Bedford 1999, Magee et al. 1999). As a consequence of the species establishment focus for mitigation, recent national and regional research indicates that mitigation processes have resulted in wetlands with reduced functional values (Niswander and Mitsch 1995, Galatowitsch and vanderValk 1996, National Research Council 2001) potentially caused by the many interpretations of the phrase "restoration success"(Kentula 2000).

Additionally, reports that examine the oversight of success also indicate deficiencies in the regulation program, citing frequent failures in permitees adherence to permit requirements and enforcement of the terms of granted permits (National Research Council 2001, Government Accountability Office 2005).

The combination of historic wetland losses and regulation, the difficulties in tracking wetland status, and the deficiencies in the wetland restoration program illustrate the challenges faced by the current task of wetland regulation in the U.S. Successful approaches for improving subalpine wetland conservation and management must consider this regulation background in order to be effective.

Research Objectives

The preceding discussion illustrates the distribution, function, and threats to subalpine wetlands and provides a brief look at wetland regulations that guide the conservation and management of these ecosystems. This information highlights the importance of improving upon baseline knowledge of the structure and function of subalpine wetlands, to ensure appropriate management decisions and future restoration success.

Although the literature examines the many characteristics and values of subalpine wetlands, it does not clearly illustrate the structural and functional characteristics which may further define theses wetland types (Windell et al. 1986, Gage and Cooper 2007). Additionally, the wetlands in these publications lack the unique structural characteristic exhibited by the wetlands of this study.

The goal of this research is to expand upon the existing knowledge of subalpine wetlands in both undisturbed and restored states, in order to provide a rigorous definition for purposes of appropriate management and conservation. The primary components of this study include:

1. Defining and comparing undisturbed conditions of subalpine wetlands
2. Examination of environmental drivers of undisturbed wetlands
3. Comparison of restored subalpine wetland to undisturbed subalpine wetlands

The above goals were selected to address the following objectives:

1. Describe the structural and functional characteristics of subalpine wetlands in an undisturbed state. Compare the characteristics of the two distinct wetland types in the study area to examine their environmental conditions and roles in the landscape.
2. Specifically examine the unique soil structure of subalpine wetlands, in order to explore the resultant hydrology of the sites.
3. Identify the environmental conditions of undisturbed subalpine wetlands that most significantly influence the functional attributes of these features.
4. Examine the response to restoration where differing techniques have been employed.

Study Area

The study area included wetland sites located on the property of Moonlight Basin Ski Area, a privately held residential and recreational development located in the

Madison Range in southwest Montana (Figure 2). The study sites are located along perennial waterways which flow in a northerly direction as tributaries to Jack Creek, and ultimately the Madison and Missouri Rivers. Sites range in elevation from 2241 m to 2324 m.

The geology of the area is predominately characterized by Upper Pleistocene glacial till parent material. Limited occurrences of additional parent material include interbedded sandstones, mudstones and shales with some porphyritic dactite (mixture of volcanic rock and plagioclase) from Upper Cretaceous volcanism (USGS 2000). Soils are characterized by clayey residuum or coarse loamy colluvium from granite, gneiss, and/or glacial till (NRCS 2008b).

The climate of the area is typical of subalpine regions, both in terms of temperature ranges and precipitation patterns. Average May temperatures range from -1.0 to 9.9 °C, while average August temperatures range from 7.4 to 19.5 °C. Average precipitation of 79.1 cm falls mostly as snow during fall, winter and spring (NRCS 2008a). SNOTEL data for 2007 in the area of Lone Mountain is indicated in Figure 1.

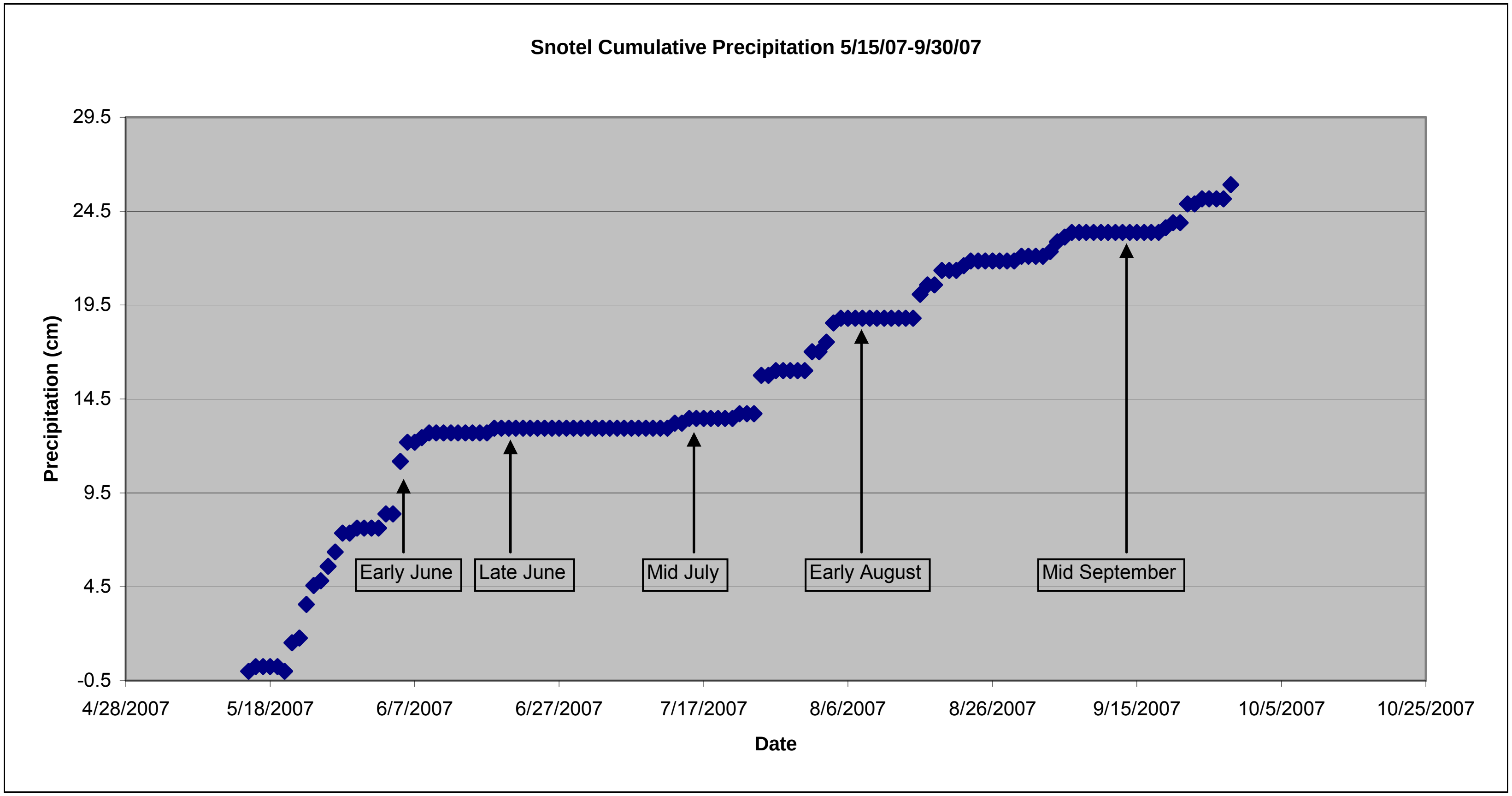

Figure 1: Cumulative precipitation for the 2007 sampling season, with water parameter sample dates indicated (NRCS 2008a).

The area is a in a subalpine spruce-fir zone, dominated by *Picea engelmannii* and *Abies lasiocarpa* in both upland and wetland/riparian sites. Understory species of upland areas are dominated by *Vaccinium spp.*, which is consistent throughout the length of the Rocky Mountains (Barbour 1988). Riparian and wetland understory communities include species associated with *A. lasiocarpa* dominance type (*Actaea rubra, Calamagrostis canadensis*) and species associated with the *P. engelmanii* dominance type (*Equisetum arvense, Senecio triangularis*) (Hansen et al. 1988).

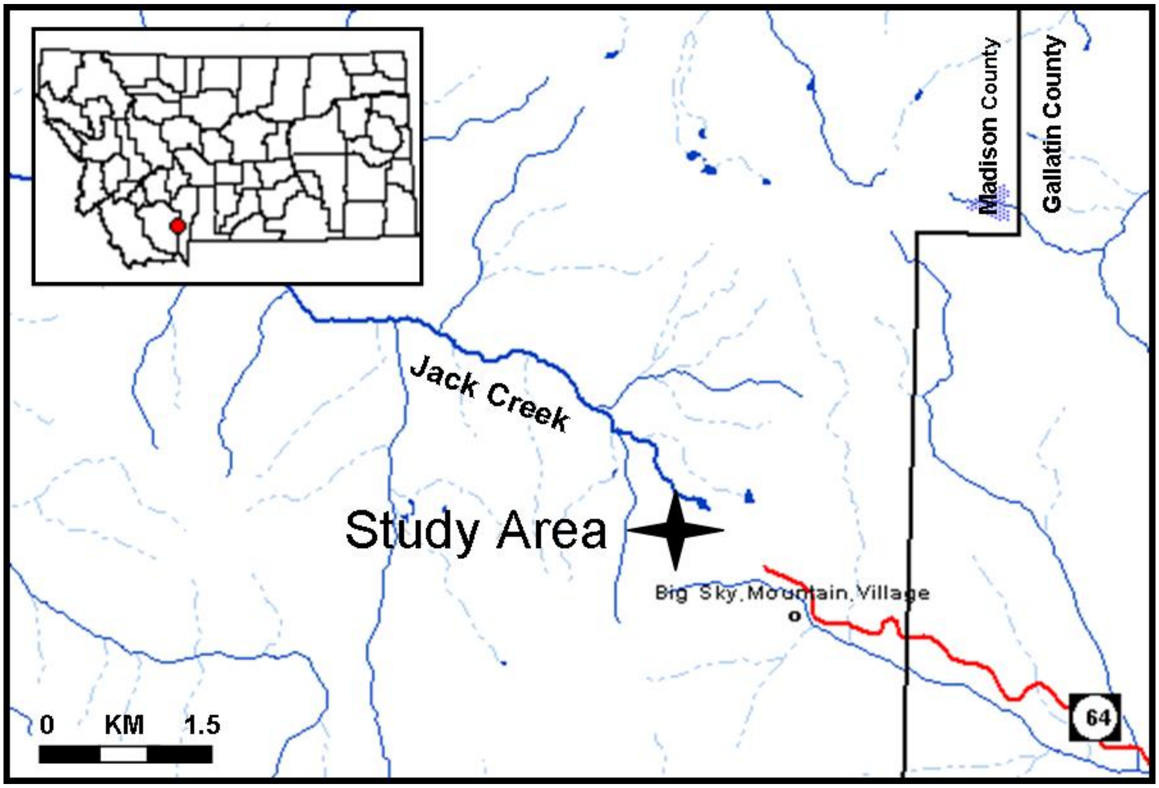

Figure 2: Map of study area showing location of study sites in relation to Jack Creek watershed and Big Sky Mountain Village.

Defining Type and Condition

Mountainous landscapes often feature varied and frequent drainages, typically a consequence of changing topography and spring activity. Sites in this study area are no exception, where 4 distinct drainages, numerous springs, and 2 distinct wetland types occur within a relatively small area.

The terms linear and depressional were used to define the different wetland types selected for the study. The distinction between the two types is primarily a function of geomorphology, and is best illustrated by the width and slope of the wetland (Figure 3). Many researchers refer to these wetland complexes as “string of pearls” wetlands, where a depressional wetland is linked via a linear wetland to the next depressional wetland, and so forth through the landscape.

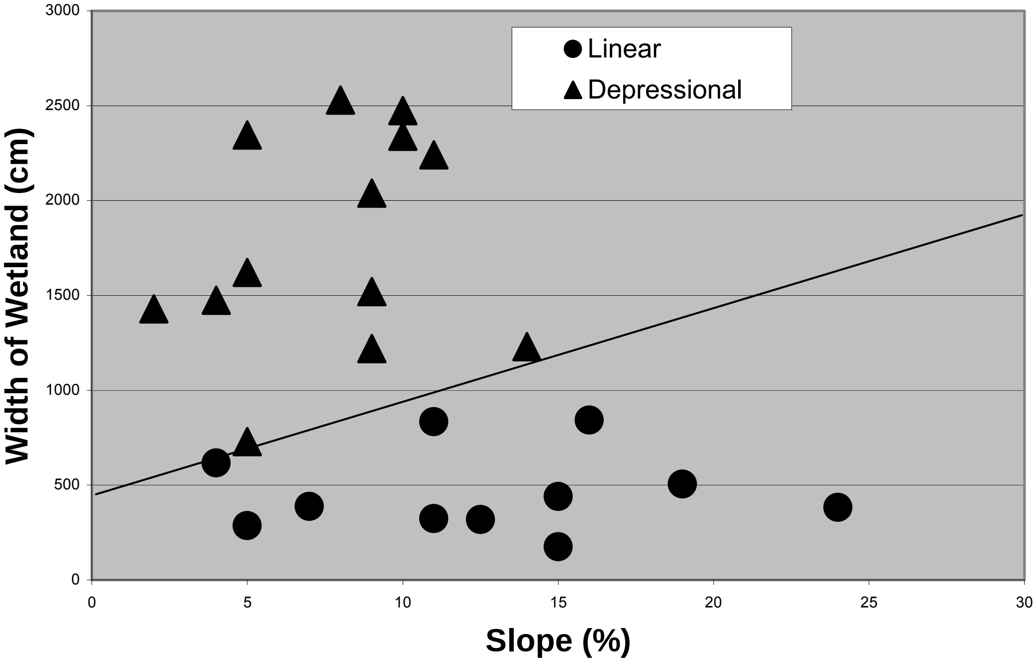

Figure 3: Graph of depressional and linear wetland types plotted by width and slope of site.

To a lesser extent, the absence or presence of a distinct channel also influenced the decision on how to categorize a site (Figure 4, Figure 5). Although the terms linear and depressional are common classifiers of wetland types (Brinson 1993a), the terms provide a coarse level of resolution due to a wide range of geomorphic settings and hydrologic influences. In most research and classification, the term "linear" is associated with riverine environments and "depressional" is associated with low slope, basin environments.

Wetland sites were further classified as either undisturbed or restored. Restored sites include recently manipulated linear and depressional wetland types, with work being completed in 2005 and 2006. The single depressional site a mitigation effort, intended to compensate for wetland impacts on other areas of the property. The mitigation wetland was created adjacent to an existing wetland by lowering the topography of the surrounding slope to match the elevation of the existing wetland. Wetland sod was then placed on the lowered area, with additional plantings of woody species installed.

The 3 linear sites underwent a process of restoration to mitigate for unpermitted placement of fill in the wetlands. Impact to these sites resulted from construction of a ski run, where unpermitted fill (logs and soil) was placed in the wetland to serve as a temporary culvert. Restoration included removal of the unpermitted fill and placement of a permanent culvert. The 3 sites in this study are located on upstream or downstream ends of the culvert, where efforts were made to remove unpermitted fill and expose the original soil and vegetation. Some planting and broadcast seeding was also completed at these sites.

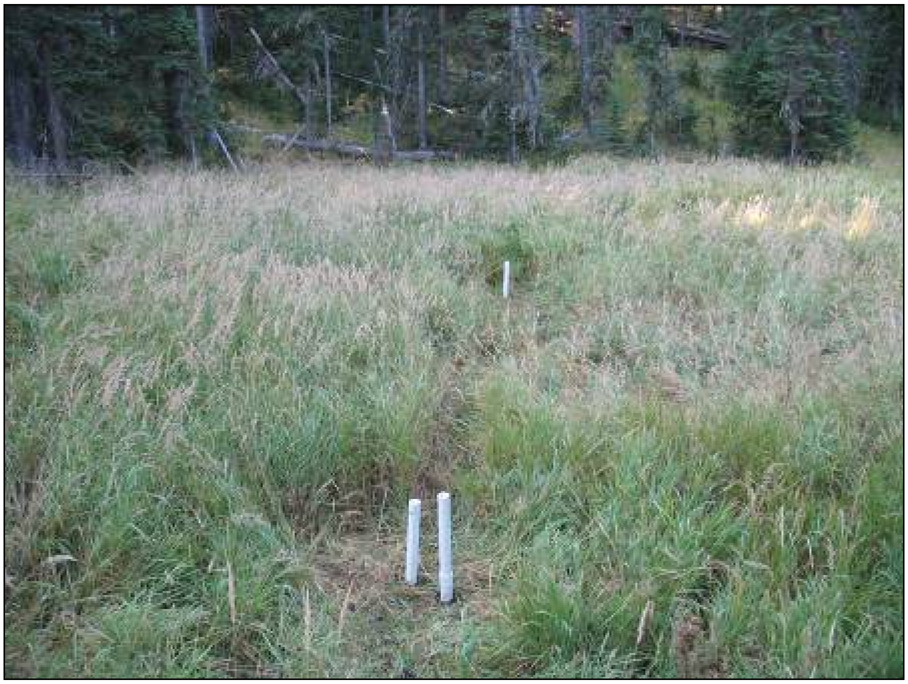

Figure 4: Photo of typical depressional wetland. Notice significant width, low slope, and lack of distinct channel.

Figure 5: Photo of typical linear wetland. Notice narrow width, higher slope, and presence of distinct channel.

METHODS

Sample Area Selection

A limited number of restored sites are sparsely located on a large area of the property. While some restored sites are characterized by perennial flows and a defined wetland plant community, other sites are characterized by ephemeral flows that do not support wetland plant communities. Only the former type was included in the study, to adhere to the objectives of examining landscape features that meet the regulatory definition of a wetland.

Twenty eight wetlands located in 4 drainages were included in this study. The undisturbed sites included 11 linear and 13 depressional wetlands, while the restored sites included 3 linear and 1 depressional wetlands.

The selected restored sites in this study were chosen for their proximity to other restored sites, in an effort to focus the study area on a small number of similarly influenced drainages. Undisturbed sites were selected for their location in relation to restored sites, in an effort to include undisturbed sites in the selected drainages above and below restored sites.

Sampling Methodology

Parameter Selection

To characterize the physical, biological and chemical conditions of the wetlands, data were collected for landscape, vegetation, soil and water parameters (Table 1). Data were collected at two levels, to examine the individual wetlands and to examine points within the wetlands. Individual wetlands are referred to as sites and areas within the wetland are referred to as locations (Figure 6).

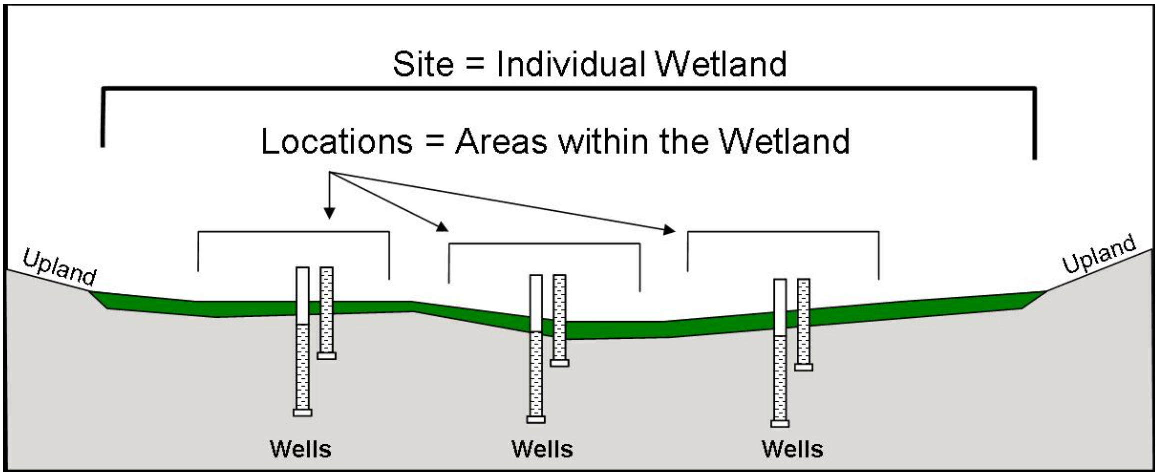

Figure 6: Diagram of site and location sampling approach.

Landscape parameters included position and exposure of the sites in the greater landscape, while providing specific information about morphology of the site. Elevation, slope and aspect influence localized precipitation patterns and sunlight availability.

Vegetation parameters included canopy cover at the site level, and species' cover, species diversity, species richness, community wetland indicator score (WIS), and biomass at the location level.

Soil data were collected at the location level only and included chemical and developmental processes that occur at the 10 and 20 cm depths of plots within the wetland. These included oxidation reduction potential (redox), pH, moisture, texture and total organic carbon.

Water parameters included stream SC at the site level, and water table depth, temperature, and SC at the location level.

Table 1: Parameters used and sampling approach for characterization.

Parameter	Level of Examination	Sampling Period(s)	Sampling Scheme
Slope	Site	Early June	Estimate for entire site
Aspect	Site	Early June	Estimate for entire site
Overstory Canopy	Site	Early June	Estimate for entire site
Elevation	Site	Early June	Estimate for entire site
Wetland Width	Site	Early June	Estimate for entire site
Soil Total Organic Carbon	Location	Mid August	10, 20 cm depth
Soil Moisture	Location	Mid July, Mid August	10, 20 cm depth
Soil Oxidation Reduction Potential (Redox)	Location	Late June/Early July, Mid August, Mid September	10, 20 cm depth
Soil pH	Location	Late June/Early July, Mid August, Mid September	10, 20 cm depth
Soil Texture	Location	Mid August	10, 20 cm depth
Depth to Water	Location	Early June, late June, Mid July, Early August, Mid September	Shallow, Deep Wells
Water Conductance (SC)	Location	Mid June, Mid July, Early August	Shallow, Deep Wells
Water Temperature	Location	Mid June, Mid July, Early August	Shallow, Deep Wells
Stream Conductance (SC)	Site	Mid June, Mid July, Early August	If flowing water present
Cover (moss)	Location	Mid August	Average of 10 frames
Cover (vegetation)	Location	Mid August	Average of 10 frames
Cover (bare ground)	Location	Mid August	Average of 10 frames
Cover (native)	Location	Mid August	Average of 10 frames
Cover (non-native)	Location	Mid August	Average of 10 frames
Richness	Location	Mid August	Average of 10 frames
Diversity	Location	Mid August	Average of 10 frames
WIS	Location	Mid August	Average of 10 frames
Herb Biomass	Location	Mid August	Total for 5 frames
Wood Biomass	Location	Mid August	Total for 5 frames

Sampling Design

The twenty eight wetland sites were sampled 2-4 times during the 2007 growing season. Some site data, such as topography, were measured only once. Data collected at the site level gives an overall indication of the condition of the setting of the wetland, while data collected at the location level illustrates the variability of conditions within the wetland. Seventy nine wells, a combination of shallow and deep, were installed at the 28 wetland sites to monitoring water table activity. The 14 linear wetlands had 39 wells, 11 in the restored wetlands. The 14 depressional wetlands had 40 wells, 4 in the restored wetland. Wells were placed along a transect running laterally across a wetland, and were used as study locations for vegetation and soil data collection.

Landscape Sampling

Slope and aspect of each wetland site were measured with a Brunton compass. Site elevation above sea level was determined by locating the site on the USGS Lone Mountain quadrangle (USGS 1997). Topographic survey of the site was completed using a stadia rod, metric tape, and hand level. Points measured included wetland/upland boundary, wetland topography, well locations, banks of streams, topography of near-adjacent upland and any abrupt changes in topography within the wetland.

Vegetation Sampling

Overstory tree coverage was measured at the site level with a concave densiometer read in four directions from the center of the wetland and averaged for the site. Location vegetation parameters were measured in an 0.5 m x 2.0 m vegetation plot adjacent to the well or well pair. To assure rigorous sampling methodology, the plot was isolated and protected from disturbance. Within the protected vegetation plot, ten 0.5 m x 0.2 m canopy-cover frames were assessed for species composition and cover (Daubenmire 1959). From this information, additional vegetation parameters were calculated including total cover, moss cover, bare ground cover, native cover, non-native cover, species richness, Shannon Diversity Index, and community wetland indicator scores.

Species richness is calculated by totaling the number of species occurring in the sample area. The Shannon Diversity Index (SDI) is calculated through species richness and species cover values, so the abundance and evenness of different species are accounted for. The Shannon Diversity Index, H, was calculated using the following equation:

$H = -\sum P_i(\ln P_i)$ where P_i is the proportion of each species in the sample

Nomenclature of plants followed (Dorn 1984). Nativity and wetland indicator class were acquired from the USDA plants database (USDA 2008), from which wetland indicator score was subsequently calculated (Table 2). After species sampling, a randomly placed 0.5 m x 1.0 m frame was harvested and measured for herb biomass and wood biomass.

Table 2: Wetland indicator classes, associated frequency of occurrence and wetland score.

Wetland indicator class	Frequency of occurrence in wetlands	Wetland Score
Obligate wetland (OBL)	>99%	1
Facultative wetland + (FACW+)	67-99%	1.4
Facultative wetland (FACW)	67-99%	1.8
Facultative wetland- (FACW-)	67-99%	2.2
Facultative + (FAC+)	34-66%	2.6
Facultative (FAC)	34-66%	3
Facultative - (FAC-)	34-66%	3.4
Facultative upland + (FACU+)	1-33%	3.8
Facultative upland (FACU)	1-33%	4.2
Facultative upland - (FACU-)	1-33%	4.6
Obligate upland (UPL)	<1%	5

Soil Sampling

Soil pH and oxidation/reduction potential (redox) were measured at the location level three times during the sampling season; late June/early July, mid August, and early September. Measurements of pH and redox were taken at 10 and 20 cm depth, with an Orion 3 star meter equipped with an Orion refillable pH electrode and an Orion combination redox/ORP electrode.

Soil moisture percent was measured gravimetrically from samples taken in late June/early July and again in Mid August, from a depth of 0-10 cm and 11-20 cm. Samples were weighed and then dried at 46°C. Dried soil samples were analyzed by AgVise laboratories for total organic carbon content by ignition method and if sample size allowed, soil texture was determined with the Bouyoucos hydrometer method (Bouyoucos 1962, Day 1965). Samples with very high organic content often did not have enough mineral soil for the hydrometer method of textural analysis.

Although many studies examine soil organic matter content as a critical condition of the soil, research on peatland soils indicate that the standard conversion of TOC to soil organic matter (TOC*1.72) may provide false soil organic matter content levels for soil types similar to those found in our research sites (Howard 1966). Consequently, this study selected TOC as the metric by which organic constituents of the soil resource were examined.

Water Sampling

Shallow and deep wells were installed during the summer of 2006. Monitoring of the wells commenced in 2007, with additional shallow wells being installed late June 2007. Both well types were constructed and installed differently in order to examine fluctuations in shallow and deep water tables (Figure 7). Shallow wells were constructed with 2 in. (5.1 cm) perforated PVC, permanently capped at the bottom end. The intended purpose of the shallow wells was to examine the suspected perched water table, which required that they be installed with the bottom terminating in a subsurface clay layer common to most wetland sites. The perforations in the pipe of the shallow wells were exposed through the organic soil layer on top of the clay. Alternately, deep wells were installed to the depth where the water table was evident in a gravel layer below the clay layer. The perforated pipe of the deep wells was exposed to a point 20 cm below ground surface within the clay layer, at which point it was joined with 2.5 in. non-perforated PVC pipe which was sealed in the clay layer to exclude surface water intrusion.

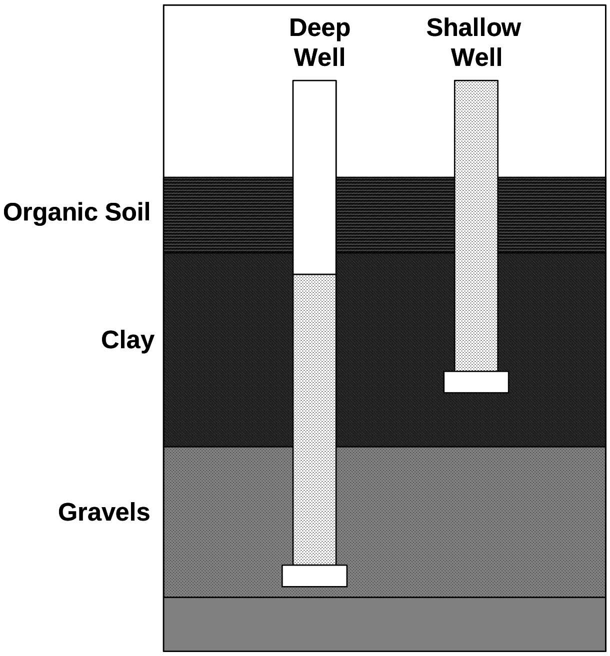

Figure 7: Diagram of deep and shallow wells. Dashed line area of wells indicates perforations.

Shallow and deep well water was measured for conductance and temperature with a MC 1 Mark V portable conductivity meter and a thermometer. The conductance measurements were corrected for temperature according to the factors provided in the conductivity meter manual, thus indicating the Specific Conductance (SC) of the water sample.

Analysis

Several analysis methods were used to understand the characteristics and processes within the wetlands. The purpose of the analyses was to characterize the two wetland types, compare wetland types and conditions, identify environmental drivers that influence the function of the wetlands, and compare the conditions of restored and undisturbed wetlands.

Characterization

Stratified and non-stratified data were employed for characterization and comparisons of wetlands. Summary statistics that included minimum, maximum, mean, and standard deviation were used to define conditions of vegetation, soil, and water parameters of the two wetland types and two wetland conditions.

Comparison

Comparison analyses were made between the two wetland types. Normality of distribution was examined through the Shapiro-Wilk test, and data failing this test were transformed using natural log function or deletion of outliers. Transformed data that passed the Shapiro-Wilk test were compared using T tests assuming equal variances. T tests that failed the Levene's test (significance < 0.05), were performed assuming unequal variances. Transformed data that failed the Shapiro-Wilk test for normality were compared using Mann-Whitney U test for non-parametric data. Due to low n values, graphical methods were used to compare the range of variability between undisturbed and restored/created sites.

Environmental Drivers

Pearson's and Spearman's correlations were used to identify significant relationships between vegetation and redox parameters (parameters used as wetland response variables) and environmental parameters (as explanatory variables) for data stratified by wetland type. Significant relationships were identified at $p < 0.05$ and $p < 0.01$ (Appendix B).

Stepwise linear multiple regressions were performed using the same vegetation and redox response variables with unforced environmental variables. A minimum n of 12 was set for parameters in multiple regressions, which eliminated the use of some soil texture and shallow well data for the analysis.

Non-stratified data were employed for a Detrended Correspondence Analysis (DCA), to examine relationships between vegetation species data and environmental data. DCA is an ordination method performed by PC Ord that quantifies similarities between locations based on species composition. The process results in data for multiple axes, which can then be used to examine relationships with other parameters. To determine environmental factors that may explain the range along an axis, first and second axes values were then included in a correlation matrix with environmental data, with significant values ($p < 0.05$) indicating the most significant environmental drivers for all of the locations (Appendix B).

Restored

Due to low n values (11 in linear, 4 in depressional), statistical analysis of restored data was not expected to be robust and was therefore not performed on these data. Graphical representations of the data distribution were completed comparing data of undisturbed locations to those of restored locations. These vertical dot plots serve to illustrate the range of variability of restored locations as compared to the range of variability of undisturbed locations.

RESULTS AND DISCUSSIONS

Defining and Comparing Natural Conditions

The practice of defining natural conditions (e.g. structure and function) of U.S. wetland types has been ongoing since federal protections were put in place. These protections rely on the accurate identification of wetlands, which requires a clear definition of conditions of wetland habitats. Publications that are applicable to wetlands throughout the US are considered paramount in the identification process (Cowardin et al. 1979, Brinson 1993a), however they do not always address some of the regional wetland variability that can occur.

Limited definitions and characterizations specific to montane and subalpine areas have been completed for the Rocky Mountain Region (Windell et al. 1986). Historic range of variability of wetland characteristics has also been completed for the many wetland types found in US Forest Service Region 2 (Gage and Cooper 2007), which includes the Rocky Mountain region in Colorado and Wyoming. These publications address various definitions of regional wetland types and summarize the functional values of the types.

Regional wetlands types have recently been the subject of structural and functional comparisons as well, by both defining the characteristics of wetland types and comparing the differences of vegetation, hydrologic and soil conditions, and chemical processes. Recent studies include comparisons of Canadian boreal wetlands (Bayley and Mewhort 2004), wetlands of the glaciated Midwest (Amon et al. 2002), and wetlands of temperate North America (Bedford et al. 1999). These studies illustrate some of the different conditions and functions of wetlands in a specific region, which is very valuable for understanding possible variability of wetland types that occupy the same region and yet often appear visibly similar.

Characterization of subalpine wetland types of the Rocky Mountains is limited. Recently, Lemly (2007) completed an assessment of fens of Yellowstone National Park, providing useful metrics for soil conditions and plant species assemblages (vascular and bryophyte) and the influence of geology and climate on fen wetland conditions of Yellowstone National Park. Lemly's study did not, however, examine the temporal variability of fen wetlands, which may further define wetland structure and function.
To build on the characterization of wetlands in earlier studies, this study collected data at two levels (1) of individual wetlands and (2) across wetlands, and at two time frames (1) single visit sampling (e.g., topography) and (2) seasonal sampling (e.g., soil redox), the latter to understand temporal variability among wetland types.

This section of the results addresses the first objective of the research, to describe the structural and functional characteristics of subalpine wetlands in an undisturbed state and compare the characteristics of the two distinct wetland types in the study area to examine their environmental conditions and roles in the landscape.

Site Characterization and Comparison

Data collected at the site level included landscape characteristics and water chemistry (SC) of the stream associated with individual wetlands. Data in Table 3 illustrate the range of external conditions influencing these wetlands, and are useful for wetland characterization at the site level.

Elevation ranged from 2247 m to 2316 m with linear and depressional sites located evenly throughout this range. Depressional sites had slope values ranging from 2%-11% while linear sites had slope values shifter toward the higher end of the range (4%-24%). Aspect was centered on northerly exposures, and ranged from 271°-124°. Canopy cover ranged from 0.25% to 29.25%, with no range specific to either wetland type. Width ranged from 175 cm to 835 cm in linear sites and 729 cm to 2530 cm in depressional sites.

Creek SC for linear and depressional sites was not significantly different during any time of the sampling season. The majority of sites (23/25) had SC values between 100 and 400 μS/cm. Only 1 site had SC below 100 μS/cm (June measurement for site 4A), and 1 site was above 400 μS/cm (July and August measurements for site 1A).

While mid and late summer (July and August) creek SC values were consistently higher than June, neither month was consistently highest. July SC values were highest in four of the sites with measurable flows throughout the season, while August SC values were highest at 10 sites.

Creek SC measurements also illustrate instances where creek flows were so reduced to prevent sampling (as indicated by blank cells in Table 3). Of the 10 sites that exhibited reduced flows, only two were linear wetlands while eight were depressional. Additionally, 4 sites with reduced flows in July exhibited a resumption in flows during August.

Table 3: Description of individual undisturbed wetlands and their associated landscape characteristics

Wetland	Type	Condition	Elevation (m)	Slope (%)	Aspect (°)	Canopy Cover (%)	Width (cm)	Creek SC June (µS/cm)	Creek SC July (µS/cm)	Creek SC August (µS/cm)
1A	Linear	Undisturbed	2309	19	341	16	505	239.75	408.1	418.91
1B	Depressional	Undisturbed	2297	9	351	28.5	1220	216.05	271.7	303.15
1C	Linear	Undisturbed	2287	16	311	26.5	842	213.15	296.1	280.85
1D	Linear	Undisturbed	2273	15	60	20.5	175	217.36	288.6	316.54
1E	Depressional	Undisturbed	2256	11	274	17	2242	169.88	315	317.2
1F	Depressional	Undisturbed	2247	10	274	12.25	2475	165.2	254.98	
2A	Depressional	Undisturbed	2309	5	19	16	1622	157.55	184.8	236.88
2B	Linear	Undisturbed	2307	5	271	27.5	287	149.5	184.6	212.8
2E	Depressional	Undisturbed	2290	5	357	11.25	729	166.05		195.92
2F	Depressional	Undisturbed	2288	14	357	10.25	1230	139.7	158.72	224.75
2G	Linear	Undisturbed	2282	24	355	13.25	382	162.15		
2H	Depressional	Undisturbed	2278	10	289	10	2340	136.64		262.01
2I	Depressional	Undisturbed	2261	9	39	6.25	1521	139.2	204.14	187.69
3A	Depressional	Undisturbed	2319	9	27	9.25	2040	142.48		
3B	Linear	Undisturbed	2307	11	14	22	323	178.8	202.8	229.46
3C	Depressional	Undisturbed	2299	2	124	17	1429	148.8		
3D	Linear	Undisturbed	2297	12.5	27	10	319	171.35	193.7	188.5
3E	Linear	Undisturbed	2289	4	1	24.5	617	145.95	182.28	188.5
3F	Linear	Undisturbed	2286	15	328	12	440	169.05	183.75	192.85
4A	Depressional	Undisturbed	2324	5	357	1.75	2346	17.76		
4B	Depressional	Undisturbed	2316	4	350	0.25	1475	159.72		192.4
4D	Linear	Undisturbed	2309	11	282	11	835	135.2		155.4
4E	Linear	Undisturbed	2303	7	300	29.25	388	160.95	378.2	208
4F	Depressional	Undisturbed	2300	8	290	8.5	2530	174.96		

Location Characterization and Comparison

Multiple locations are established within a site. Data collected at the location level include metrics recorded single or multiple times during the sampling season, and provide an indication of the conditions at each of the well or well pair sites across a wetland.

Vegetation: Table 4 provides several metrics by which the vegetation of subalpine wetlands is characterized and compared. Vegetation parameters in this study include both structural (e.g. species composition) and functional metrics (e.g. biomass).

Mean cover indicates that linear and depressional locations support ~80% cover of vascular plant species and ~12% cover of mosses (bryophyte species). Mean bare ground cover for linear wetlands was ~11% and for depressional ~7%, with linear sites having greater variability. The majority of these species are native, with low non-native cover values (mean <3%) for both wetland types.

Table 4: Summary statistics for vegetation parameters displayed by wetland type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-parametric data. Significant values ($p < 0.05$) of comparisons of parameters between the two wetland types are bold and underlined.

		Linear				**Depressional**				
Vegetation Parameters	**Units**	**Min**	**Max**	**Mean**	**+/- SD**	**Min**	**Max**	**Mean**	**+/- SD**	**Sig.**
Vegetation Cover	(%)	43.00	102.50	79.58	16.03	45.25	117.50	79.85	15.31	.947
Moss Cover	(%)	0.25	46.50	12.27	13.03	0.25	41.50	11.41	11.59	.983
Bare Ground Cover	(%)	0.25	51.75	11.04	15.95	0.25	28.00	7.00	6.39	.908
Wetland Indicator Score		1.46	3.10	2.26	0.41	1.24	3.02	2.11	0.47	.174
Richness	(#/1.0m^2)	8.00	25.00	16.00	3.52	4.00	23.00	13.65	4.85	**.019**
Shannon Diversity Index		1.10	2.72	2.12	0.33	0.96	2.60	1.92	0.44	**.008**
Non-Native Veg Cover	(%)	0.25	10.50	2.83	3.51	0.25	4.00	1.21	1.34	.294
Native Veg Cover	(%)	37.75	102.50	78.05	16.04	45.25	117.50	79.45	15.18	.718
Herb Biomass	(g/m^2)	29.80	287.90	89.37	56.14	24.80	308.70	131.48	72.07	**.013**
Wood Biomass	(g/m^2)	1.60	536.20	70.91	136.89	1.10	15.60	7.49	6.74	.140

The minimum, maximum and standard deviation for WIS were very similar between the wetland types. Mean WIS is for linear (2.26) and depressional (2.11) locations is equivalent to vegetation with a FACW- (Facultative Wetland –) wetland indicator class (Table 2). This class has a frequency of occurrence in wetlands between 67% and 99%. Mean species richness for linear and depressional wetlands is 16 and 13.7 respectively, with depressional sites having greater variability. Mean SDI was 2.1 for linear locations and 1.9 for depressional locations.

Although minimum and maximum herb biomass values were very similar, mean values were (89.4 g/m^2) for linear and (131.5 g/m^2) for depressional locations. Wood biomass was highly variable for linear locations and very limited at nearly all of the depressional sites.

Significant differences between wetland types exist for species richness, SDI, and biomass (Table 4, Figure 8). Species richness and Shannon Diversity Index (SDI) are significantly higher in linear wetlands than depressional wetlands, indicating a greater number of species in linear wetlands that are more equally distributed. Herb biomass was conversely higher in depressional sites, indicating greater above ground plant production.

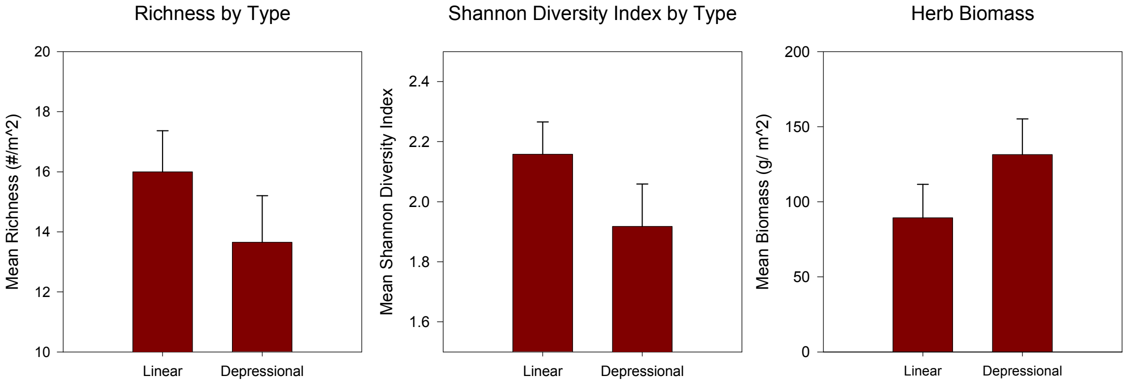

Figure 8: Graphs illustrating vegetation parameters that are statistically significant between linear and depressional wetlands. Bars indicate 95% confidence interval.

The species list for all sites is found in Appendix A. The range of cover and frequency of plant species within the wetland communities is shown in Figure 9. Although this figure is not a statistical examination, it does provide patterns of species composition for linear and depressional wetlands. This figure illustrates similarities and differences of all species recorded for the locations, dominant species (individuals with frequency >0.5 and cover > 2.0, shown in shaded rectangle), and the dominant communities (all species as a group with frequency >0.5 and cover > 2.0) in linear and depressional locations.

Similarities in community composition are illustrated by species that are dominant within the communities and those that are non-dominant. Species that are non-dominant have low cover and frequency values and therefore tend to be arranged in the same location on the figures.   Species that are dominant in the communities (shown in blue shaded rectangle) include 7 species for linear and depressional locations, 6 of which are shared between the two wetland types. The dominant species include *Aster foliaceus, Calamagrostis canadensis, Equisetum arvense, Geranium richardsonii, Mitella pentandra,* and *Senecio triangularis* for both linear and depressional locations. Linear locations also include *Arnica mollis* as a dominant species, while depressional locations include *Fragaria virginiana* as a dominant species.

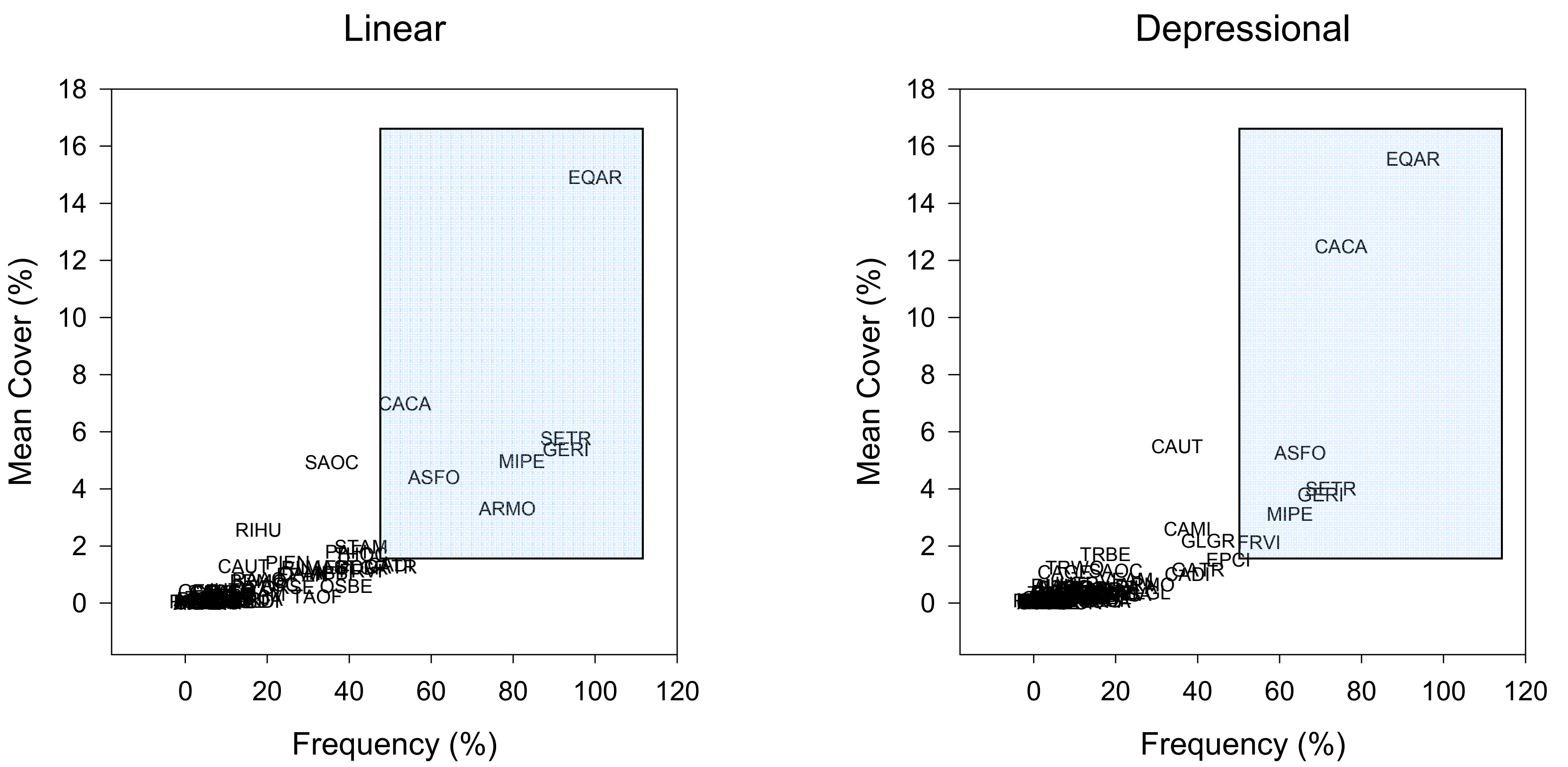

Figure 9: Relationship between species cover and frequency for linear and depressional wetlands. Graphs plot mean cover per location (%) and frequency (% of plots) for each species, represented by species symbol. Shaded box defines the dominant community (all species with a frequency > 50% and cover >2%).

Soil: Several metrics were used to characterize and compare the chemical and physical characteristics of soils of subalpine wetlands Table 5. These soil parameters include both functional (e.g. redox) and structural (e.g. texture) metrics.

In both wetland types, mean redox values during all sample periods and at both sample depths occur in a narrow range with all values between 118 and 190 mv. Both wetland types are defined by a highly variable range of redox values. Depressional wetlands had lower mean redox values, more redox values in the highly reduced (anaerobic) state (< -100 mv), as well as the sole value in an oxidized state (> 400 mv).

Mean soil pH of linear and depressional locations is moderately acidic at both 10 and 20 cm depths, with minimum values of strong acidity for both depths and types. Maximum pH for linear locations is weighted toward slightly alkaline values, while maximum pH for depressional locations weighted toward slightly acidic values.

Mean soil moisture content ranged from 42.0 to 52.3 % of dry weight for linear locations, and 54.5 to 69.3 % for depressional locations. Minimum values were similar between the wetland types while maximum values for linear locations were mostly around 80% and depressional locations were mostly around 90%. Mean moisture values were consistently higher at 10 cm depth during July and August for both linear and depressional locations.

Mean TOC at 10 cm depth in linear locations is 13.2, while mean TOC at 10 cm for depressional locations is 18.9. Mean TOC at 20 cm depth for linear locations is 7.2, while mean TOC at 20 cm in depressional locations is 11.0. Depressional locations had greater minimum and maximum TOC values at both 10 and 20 cm depths.

Table 5: Summary statistics for soil parameters displayed by wetland type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-normally distributed data. Statistically significant values ($p < 0.05$) are bold and underlined.

		Linear				**Depressional**				
Soil Parameters	**Units**	**Min**	**Max**	**Mean**	**+/-SD**	**Min**	**Max**	**Mean**	**+/-SD**	**Sig.**
Redox July 10 cm	mv	-70.60	352.00	172.55	111.18	-119.50	380.40	139.17	121.91	.254
Redox July 20 cm	mv	-57.00	355.40	164.50	114.89	-141.30	296.00	119.37	126.68	.257
Redox Aug 10 cm	mv	-17.80	357.80	189.86	89.83	-212.00	305.80	129.52	142.92	.170
Redox Aug 20 cm	mv	-59.40	340.50	165.55	108.44	-150.50	333.20	118.92	130.41	.125
Redox Sept 10 cm	mv	-188.40	344.90	182.74	126.43	-199.90	385.90	118.24	132.84	**.002**
Redox Sept 20 cm	mv	-241.20	301.70	143.85	145.37	-206.13	489.10	130.95	145.10	.356
pH July 10 cm		3.96	7.45	5.92	0.71	4.58	6.98	5.88	0.56	.576
pH July 20 cm		4.74	7.29	5.88	0.67	4.48	7.25	5.73	0.59	.339
pH August 10 cm		4.27	7.17	6.07	0.62	5.06	7.10	6.03	0.43	.606
pH August 20 cm		4.45	7.45	5.98	0.58	5.12	6.62	5.76	0.35	.084
pH Sept 10 cm		4.92	7.09	6.08	0.53	5.34	6.83	6.08	0.35	.992
pH Sept 20 cm		4.95	6.89	6.10	0.43	4.87	6.89	5.98	0.44	.253
Moisture July 10 cm	(% weight)	16.85	82.15	48.75	17.92	21.56	88.34	64.79	17.39	**.000**
Moisture July 20 cm	(% weight)	10.41	82.24	42.07	19.09	15.50	88.45	54.47	20.19	**.000**
Moisture Aug 10 cm	(% weight)	28.10	81.06	52.28	17.48	34.26	89.09	69.24	14.97	**.000**
Moisture Aug 20 cm	(% weight)	23.08	78.42	43.13	16.57	14.35	89.75	56.10	20.24	**.006**
TOC 10 cm	(% weight)	0.55	30.36	13.24	8.28	6.30	37.64	18.85	8.46	**.011**
TOC 20 cm	(% weight)	1.05	23.65	7.23	6.35	2.43	30.19	10.99	8.78	**.016**
Sand 10 cm	%	31.00	61.00	45.67	10.42	27.00	31.00	28.50	1.91	**.000**
Silt 10 cm	%	16.00	36.00	26.33	6.31	27.00	33.00	31.00	2.71	.181
Clay 10 cm	%	21.00	37.00	28.00	5.15	36.00	46.00	40.50	4.20	**.001**
Sand 20 cm	%	27.00	67.00	43.09	11.10	19.00	45.00	30.55	6.67	**.000**
Silt 20 cm	%	14.00	42.00	28.45	7.14	16.00	38.00	27.95	6.26	.854
Clay 20 cm	%	15.00	59.00	28.45	12.08	19.00	59.00	40.59	11.59	**.001**

Significant differences of soil characteristics between wetland type exist in 11 of the 24 parameters (Table 5, Figure 10). Similar to vegetation parameters, this is a minority of parameters that show significant differences. Soil moisture at 10 and 20 cm was higher in depressional locations during both July and August. TOC was also higher in depressional locations at both 10 and 20 cm depths.

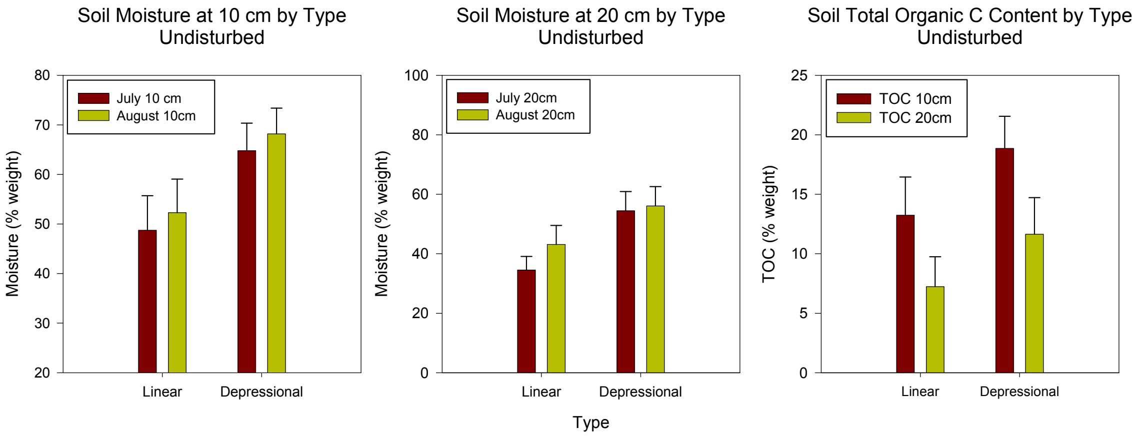

Figure 10: Graphs illustrating soil parameters that are statistically significant between linear and depressional wetlands. Whiskers indicate 95% confidence interval.

The other soil chemistry parameters (pH, redox) were, with a single exception of one sample date, not significantly different between the two wetland types. Redox values for linear and depressional locations were found to only be significantly different during September at 10 cm.

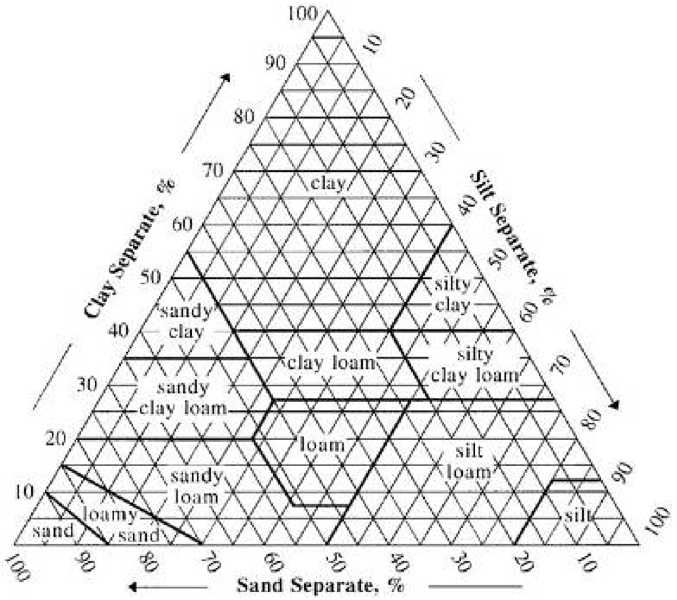

Figure 9: Soil texture triangle for identification of major soil textural classes

Figure 9 illustrates how texture is defined by the proportion of the soil resource composed of silt, sand and clay particles, with soil type nomenclature corresponding to specific ranges of these proportions.

Most soil texture composition values at both 10 and 20 cm depth for linear locations place the soils in the clay loam soil categories while those for depressional locations at 10 and 20 cm depth are in the clay soil type category. Linear locations had consistently greater variability at both 10 and 20 cm depths for sand, silt and clay soil components.

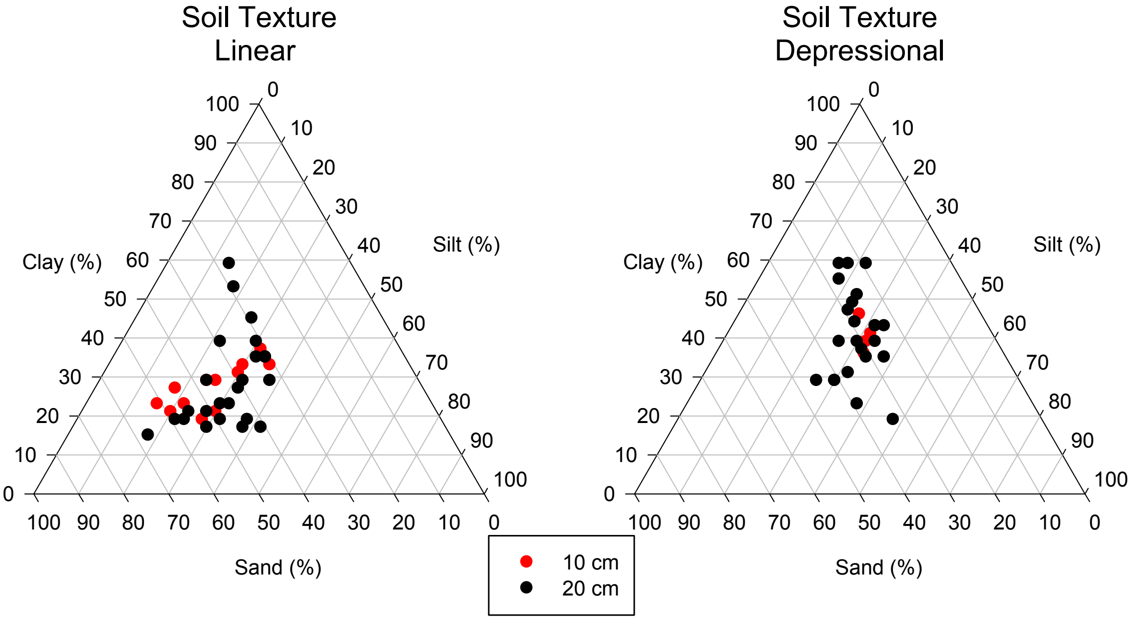

Figure 11: Comparisons of soil texture data showing differences between linear and depressional wetlands. Statistical tests show textural differences between wetland type are significant at p>0.05.

Significant differences in clay and sand content are seen at both the 10 and 20 cm depths in depressional and linear locations (Table 5). Figure 11 illustrates the tendency for depressional locations to have lower sand and higher clay content.

Water: Several metrics were used for comparison of water characteristics of subalpine wetlands (Table 6 - Table 8). These included water table depth and fluctuations, temperature and conductance (SC).

Water Temperatures. Mean well water temperatures for both linear and depressional locations occupied a narrow range (10.8°C to 15.1°C), had similar narrow ranges of variability (<2.6 for linear and <1.8 for depressional), and similar minimum and maximum values (Table 6). Shallow well water temperatures were consistently greater than deep well water temperatures, and depressional locations consistently had higher mean temperatures in both well types than did linear locations during the same sampling period.

Significant differences between wetland type occur in both June and July deep and shallow well water temperatures (Table 6). During these periods, depressional locations had higher mean well water temperatures than did linear locations.

Table 6: Summary statistics for water temperature displayed by wetland type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-parametric data. Statistically significant values ($p < 0.05$) are bold and underlined.

		Linear				**Depressional**				
Water Parameter	**Units**	**Min**	**Max**	**Mean**	**+/- SD**	**Min**	**Max**	**Mean**	**+/- SD**	**p**
Temp Deep Wells June	°C	8.00	14.00	10.79	1.75	8.00	15.00	12.04	1.76	**<u>.006</u>**
Temp Shallow Wells June	°C	10.50	14.00	12.25	2.02	12.00	17.00	15.08	1.83	**<u>.042</u>**
Temp Deep Wells July	°C	7.50	17.00	11.63	2.36	9.50	16.00	13.56	1.77	**<u>.010</u>**
Temp Shallow Wells July	°C	9.00	14.00	11.86	1.68	10.50	16.50	14.21	1.76	**<u>.008</u>**
Temp Deep Wells Aug	°C	7.00	16.00	10.87	2.17	9.50	13.00	11.51	1.04	.137
Temp Shallow Wells Aug	°C	7.00	17.00	11.53	2.60	9.50	14.00	11.73	0.99	.686

*Water SC***.** As noted for the creek SC values, the mean well water SC values are all <333. There were no significant differences in well SC between wetland type during any time of the year (Table 7). Deep wells of both wetland types had a greater range of variability for SC than did shallow wells.

Table 7: Summary statistics for water SC displayed by wetland type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-parametric data. Statistically significant values ($p < 0.05$) are bold and underlined.

		Linear				**Depressional**				
Water Parameter	**Units**	**Min**	**Max**	**Mean**	**+/- SD**	**Min**	**Max**	**Mean**	**+/- SD**	**p**
SC Deep Wells June	µS/cm	140.97	424.65	234.53	80.78	41.72	332.80	199.86	69.58	.182
SC Shallow Wells June	µS/cm	156.21	243.25	190.13	37.22	152.50	361.76	217.29	68.97	.485
SC Deep Wells July	µS/cm	26.79	623.50	246.05	123.34	27.36	475.08	239.99	94.91	.723
SC Shallow Wells July	µS/cm	164.40	365.40	280.07	74.14	168.19	539.40	333.08	86.03	.151
SC Deep Wells Aug	µS/cm	26.30	398.75	224.81	90.63	25.38	345.80	206.83	64.09	.356
SC Shallow Wells Aug	µS/cm	182.90	397.62	267.41	70.63	136.40	385.70	239.79	62.33	.125

*Water Tables***.** Data from water table measurements have been analyzed two ways. One is actual levels and how they fluctuate over time, and the other, related to this, is the persistence of the water table within 30 cm of the ground surface, the depth within which most wetland plant roots occur. The persistence of shallow water is discussed first because period and length of inundation is perhaps the most critical influence to wetland plant growth and survival.

Persistence of Shallow Water. Figure 12 - Figure 15 show the number of wells by wetland type with measurable water table levels within 30 cm of surface for number of days of the growing season (May 15-September 15). This illustrates duration of near surface saturation as a result of water table fluctuation. Linear wetlands contained 21 shallow wells and 28 deep wells, while depressional wetlands contained 37 shallow wells and 39 deep wells.

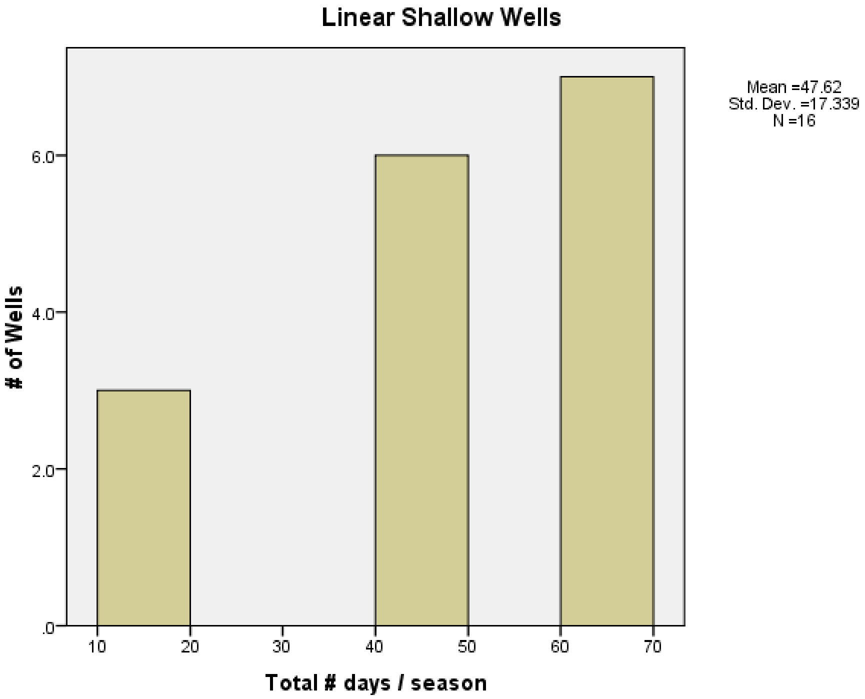

Figure 12: Number of linear wetland shallow wells with measurable water table levels within 30 cm of surface for a number of days of the growing season (e.g., 20 days is the number of days of inundation between May 15 and September 15).

Figure 12 illustrates that a total of 16 shallow wells (76%) at linear locations had water within 30 cm of surface for some part of the growing season. Of these wells, 3 had water for less than 20 days, 6 had water between 40 and 50 days and 7 had water between 60 and 70 days.

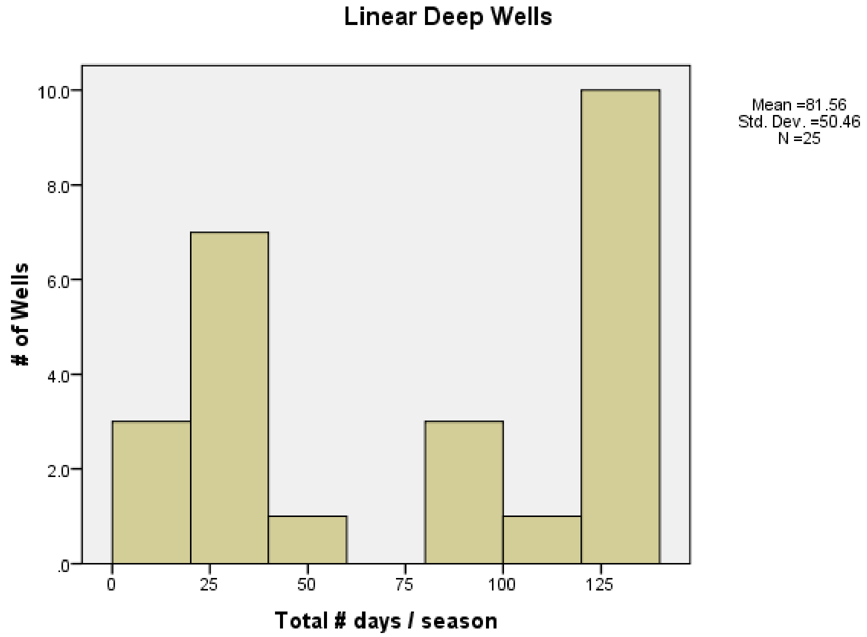

Figure 13: Number of linear location deep wells with measurable water table levels within 30 cm of surface for a number of days of the growing season (e.g., 20 days is the number of days of inundation between May 15 and September 15).

Figure 13 provides a description of shallow water table activity for deep wells of linear wetlands, where 25 (89%) had water within 30 cm of the surface. While 11 wells had water for up to 65 days, 10 wells had water for greater than 120 days (120 days is considered the length of the growing season.) The number of wells with shallow water during the interim period of 40 – 120 days was only 5 wells. For deep wells, the majority of occurrence of shallow water was for the shortest and longest durations with mid-range duration showing little shallow water table activity.

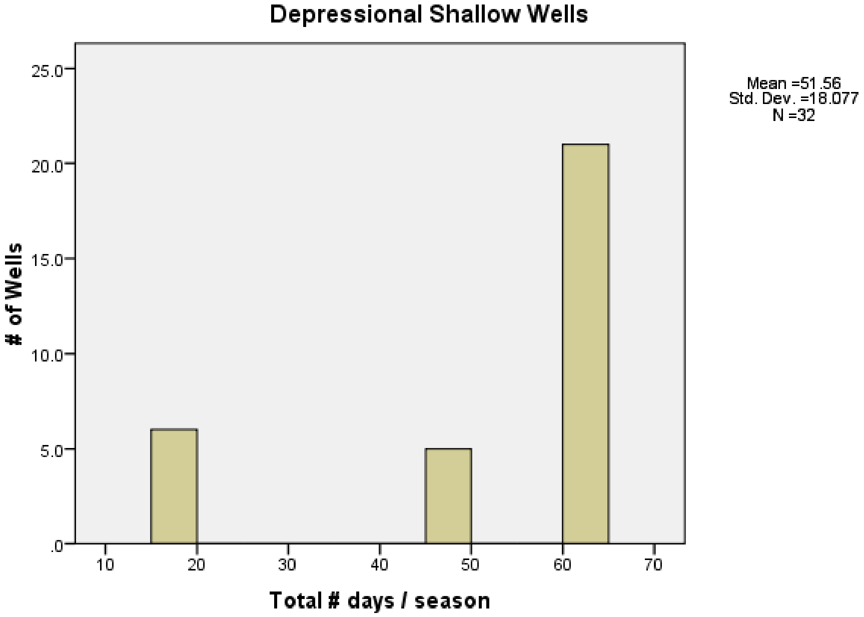

Figure 14: Number of depressional location shallow wells with measurable water table levels within 30 cm of surface for a number of days of the growing season (e.g., 20 days is the number of days of inundation between May 15 and September 15).

Figure 14 illustrates water table activity for shallow wells of depressional locations, where 32 (87%) had water within 30 cm of surface. Over half (21) had water for greater than 60 days, 5 had water between 40 and 50 days, and 6 had water for less than 20 days. In comparison to the 7 linear wells in the 60-70 day category, the 21 depressional wells in the same category illustrate the greater persistence of shallow water associated with this wetland type.

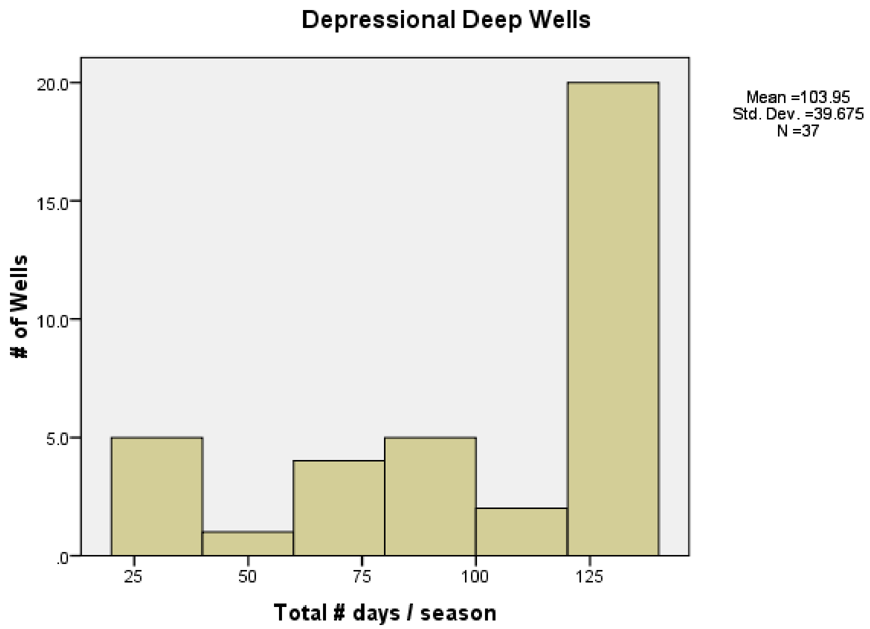

Figure 15: Number of depressional location deep wells with measurable water table levels within 30 cm of surface for a number of days of the growing season (e.g., 20 days is the number of days of inundation between May 15 and September 15).

Figure 15 illustrates water table activity of deep wells for depressional locations, where 37 (95%) had water within 30 cm of surface for some or all of the growing season. Greater than half (20) of these wells had water for greater than 120 days, as compared to only 10 wells of linear locations. The remaining 17 depressional deep wells are evenly distributed among the other categories of inundation period.

Figure 12 - Figure 15 illustrate the tendency for both linear and depressional wetlands to exhibit persistence of shallow water for a portion of the growing season. However, depressional locations exhibited a pronounced tendency (indicated by percentage of wells) to maintain saturation for a majority of the growing season.

Water Table Fluctuations. The water table fluctuation data characterize the fluctuation of water table in both wetland types, and additionally compares (1) the differences in shallow and deep water table activity between wetland types, and (2) the differences between shallow and deep wells within each wetland type. The first comparison serves to characterize water table patterns in both wetland types and addresses the theory that linear and depressional wetlands exhibit different hydrologic regimes. The second comparison addresses the theory that water table fluctuations throughout the sampling season are different at the surface of the soil then below the clay dominated substrate observed in many wetland locations of both wetland types.

Table 8: Summary statistics for water depth displayed by wetland type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-parametric data. Statistically significant values ($p < 0.05$) are bold and underlined.

		Linear				**Depressional**				
Water Parameters	**Units**	**Min**	**Max**	**Mean**	**+/-SD**	**Min**	**Max**	**Mean**	**+/-SD**	**p**
Deep Wells early June	cm	-59.20	16.00	-17.04	15.18	-34.00	8.00	-7.35	11.45	**.003**
Shallow Wells early June	cm	-17.00	-4.00	-8.63	6.16	-11.50	12.50	1.18	6.55	.032
Deep Wells late June	cm	-59.50	4.50	-21.22	15.10	-38.50	7.00	-10.12	12.16	**.007**
Shallow Wells late June	cm	-28.00	-11.50	-17.88	7.26	-6.50	11.50	0.38	5.84	**.001**
Deep Wells mid July	cm	-61.00	-0.50	-28.74	15.66	-71.80	3.50	-21.32	20.70	.075
Shallow Wells mid July	cm	-34.00	-6.50	-18.80	8.60	-26.30	10.00	-7.21	7.13	**.004**
Deep Wells early Aug	cm	-50.50	2.50	-25.50	15.78	-67.00	6.50	-15.52	16.83	**.020**
Shallow Wells early Aug	cm	-47.00	-5.70	-17.25	12.01	-30.00	11.30	-9.58	9.55	**.024**
Deep Wells mid Sept	cm	-61.50	-0.50	-31.77	16.13	-79.50	-0.50	-23.10	20.46	.070
Shallow Wells mid Sept	cm	-45.00	2.30	-21.89	12.41	-33.00	10.50	-13.16	9.56	**.012**

Mean water tables indicate water levels in both wetland types are variable throughout the year while remaining relatively near to the surface (< 32 cm) (Table 8). Water table depths for linear and depressional locations followed several similar patterns.

Mean deep well water table was consistently lower than mean shallow well water table throughout the season. Deep and shallow water table depths were nearest to the surface during early and late June. Deep wells had greater variability than shallow wells.

Minimum water table depths for shallow wells in linear locations were deeper than depressional locations throughout the season, and deep well minimum values were also further below the surface for all but 1 sample period. Linear location wells have greater overall depths and variability, while depressional locations have shallower overall depths and less variability, especially in the shallow wells.

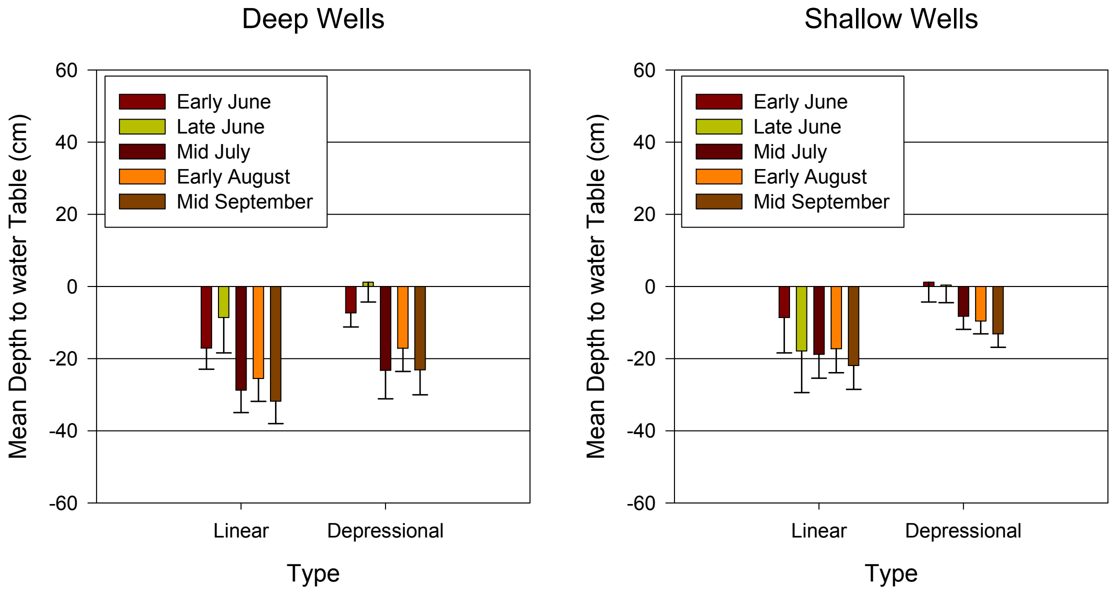

Figure 16: Bar charts grouped by wetland type showing mean and 95% confidence interval for depth to water table in deep wells (left graph) and shallow wells (right graph)

Significantly different deep well water depths between wetland type occur in early and late June, and August (Table 8, Figure 16). June depressional water table levels are at the surface, while August water depth measurements in depressional locations are nearer to the surface than are linear locations. However, depth to water table appears consistently deep in July and September.

In shallow wells, significantly different water depths between wetland type include all periods except early June (Table 8, Figure 16). Depressional locations maintain a shallow mean water table (within 15 cm of surface) for the length of the sampling season, while linear locations exhibit a deeper mean water table (> 15 cm below surface) for all periods except early June.

Descriptive statistics of water table depth are also provided in Table 9, to provide comparison between shallow and deep wells within each wetland type. The seasonal patterns are also illustrated for each wetland type in Figure 17.

Table 9: Summary statistics of water table depth displayed by well type. Statistical comparisons between wetland type were completed with t tests for normally distributed data or Mann Whitney U tests for non-parametric data. Statistically significant values ($p < 0.05$) are bold and underlined.

		Deep Wells				**Shallow Wells**				
Water Parameters	**Units**	**Min**	**Max**	**Mean**	**+/-SD**	**Min**	**Max**	**Mean**	**+/-SD**	**p**
Linear Early June	cm	-59.20	16.00	-17.04	15.18	-17.00	-4.00	-8.63	6.16	0.287
Linear Late June	cm	-59.50	4.50	-21.22	15.10	-28.00	-11.50	-17.88	7.26	0.670
Linear Mid July	cm	-61.00	-0.50	-28.74	15.66	-34.00	-6.50	-18.80	8.60	**0.024**
Linear Early Aug	cm	-50.50	2.50	-25.50	15.78	-47.00	-5.70	-17.25	12.01	0.114
Linear Mid Sept	cm	-61.50	-0.50	-31.77	16.13	-45.00	2.30	-21.89	12.41	**0.040**
Depressional Early June	cm	-34.00	8.00	-7.35	11.45	-11.50	12.50	1.18	6.55	**0.018**
Depressional Late June	cm	-50.50	7.00	-12.10	14.52	-6.50	11.50	0.38	5.84	**0.007**
Depressional Mid July	cm	-90.00	3.50	-23.23	23.39	-32.00	10.00	-8.25	8.62	**0.021**
Depressional Early Aug	cm	-74.50	6.50	-17.12	19.22	-30.00	11.30	-9.58	9.55	0.217
Depressional Mid Sept	cm	-79.50	-0.50	-23.10	20.46	-33.00	10.50	-13.16	9.56	0.191

There are statistically significant differences between shallow and deep wells for both linear and depressional locations (Table 9). Differences for linear locations include July and September, when deep well water table was recorded at the deepest mean levels for the entire sampling season. Alternately, differences for depressional locations include early June, Late June and July. During June, shallow well water depths were recorded very near or at the ground surface, while deep wells during July had very low water table levels.

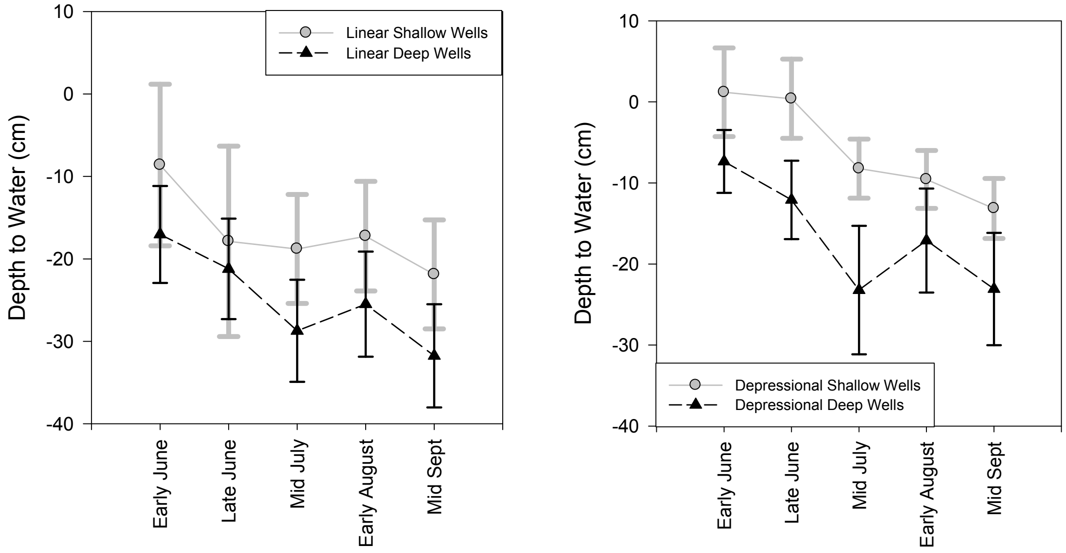

Figure 17: Depth to water table throughout the sampling season of undisturbed linear (left) and depressional (right) locations. Points indicate mean with 95% confidence interval error bars.

Complicating the prior analysis of water table activity is the fact that a number of shallow wells in both linear and depressional locations did not have a measurable water table during some times of the year. Therefore, the data discussed earlier is based on measurable wells but does not account for the absence or presence of water in the shallow wells, which is an additional useful metric for examining water table activity. In an attempt to examine this trend, the proportion of shallow wells with measurable water table depth is illustrated in Figure 18.

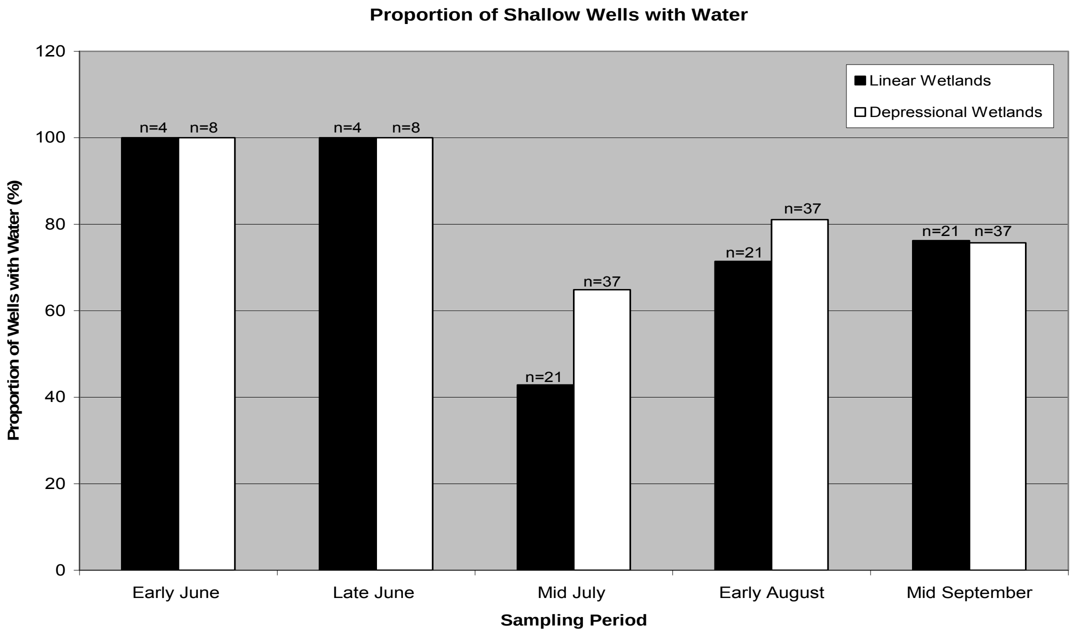

Figure 18: The proportion of shallow wells by wetland type with measurable water levels throughout the sampling season. Number of total wells sampled is shown as n values above each bar.

During early and late June, 100% of the shallow wells for linear and depressional locations had measurable water tables, while July, August, and September had reduced proportion of measurable water tables. It should be noted, however, that the number of shallow wells in linear (n=4) and depressional (n=8) locations are lower during June than the number of wells in linear (n=21) and depressional (n=37) locations during July, August, and September a result of installation of additional shallow wells in late June of 2007.

The proportion of shallow wells of linear locations that had a measurable water table was lower than that of depressional locations in July and August, but was equal to that of depressional locations in September.

Discussion

The characterization of natural conditions of subalpine wetlands is our first objective and comparison with other wetland studies should demonstrate the commonality of the parameters we examined. The characterization of linear and depressional wetlands presented illustrates the normal conditions that land managers may find in these wetland types. We found that more than half of the total parameters are significantly different between the two wetland types. This comparison provides evidence that linear and depressional wetland types of this subalpine region exhibit a different structural characteristic and have different functional roles.

For wetlands occurring in a relatively narrow elevational range, landscape parameters for slope, width, aspect, and canopy cover proved to be highly variable. The range of these values illustrates the varying landscape positions and morphological traits of these subalpine wetlands. This variability may result from the heterogeneous landscape typified in small mountainous watersheds (Schmitz 2003). Forest overstory densities were similarly variable, likely a consequence of historic land use such as logging, and the stages of growth and regrowth of the current overstory.

SC, an approximation of the concentration of dissolved solids in solution, is a common metric used in surface water quality analysis (Hem 1985). Creek SC values are likely linked to the position of these wetlands as components of headwater streams.

Similar SC values for mountain headwater streams have been shown in a compilation report for water quality monitoring programs in the state of Montana, which noted higher values of SC in the lower parts of basins as compared to those closer to mountain headwater streams (Lambing and Cleasby 2006).

The SC range of creeks associated with the study wetlands is similar to the SC of surface flows in the Centennial Valley, a region of comparable elevation and conditions in southwestern Montana (Covino et al. 2005). Creek SC in our study was lowest in June, also comparable to trends noted by Covino (2005) where increased flows during the early summer reduce the concentration of solutes in suspension (Hem 1985).

The creek SC data also indicate a trend of reduced flows, as seen by periods without creek SC data. As described in the Study Area section, depressional wetlands often lacked a distinct channel. Instead, flows occurred across the entire surface of depressional wetlands during early summer, with flows subsiding or becoming greatly reduced during drier periods later in summer (July and August). This may influence the number of sites with unmeasurable flows and thus no stream water chemistry data during late summer (particularly July). Resumption in flows was noted for some sites during August probably a result of heavy precipitation in early August which contributed to the resumption of flows in some sites that were without flows during July. This precipitation was recorded as 1.1 inches (2.8 cm) during four of the first six days of August (Figure 1).

Vegetation: Vegetation cover values were similar to other herbaceous dominated wetland communities reviewed by Windell et al (1986) where cover values similarly approached and exceeded 100%. The presence of non-native plant species in this study is believed to be the result of post-logging revegetation efforts. Historically, plantings of non-native grass species were found to be a cost effective method to provide ground cover and forage in logged and burned areas (McClure 1958).

We found several vegetation parameters to be similar to those of other montane and subalpine riparian and wetland areas. Similar WIS were recorded for seedbank germinants of floodplain areas of montane riparian ecosystems in Arizona (Richter and Stromberg 2005). Species richness values are within the range of other herbaceous dominated wetland communities reviewed by Windell et al (1986) and forb and graminoid taxa of montane riparian ecosystems (Richter and Stromberg 2005). Montane wetlands of the north cascades had slightly lower SDI, these values were correlated with wetland size and moisture regime (Risvold and Fonda 2001). Herb biomass values from this study are also similar to other studies. Windell et al (1986) cites several similar biomass values associated with montane and subalpine wetland types, including a rush dominated wet meadow (81 g/m^2) and a *Sphagnum* dominated bog (100 g/m^2). Dwire et al. (2004) recorded similarly low mean woody biomass values, consistently below mean values of graminoid species.

Significant differences between wetland types were found for species richness, SDI, and herb biomass. Linear wetlands were characterized by a narrow margin of wetland vegetation bordered on both sides by a typical subalpine upland plant community. Species richness and diversity may be higher in this setting because this narrow margin of wetland vegetation results in a greater proportion of the wetland area being adjacent to upland dominated plant communities. Consequently, the wetland fringe (the transition zone between wetland and upland dominated plant communities), may occupy a proportionately larger zone in linear wetlands than in depressional wetlands and thus support a greater range of plant species. A similar conclusion was made for montane riparian meadows by Dwire et al. (2004), who noted a positive relationship with richness and water table depth gradient away from the stream. Additionally, although we found wetland indicator scores (WIS) to not be significantly different between the two wetland types, the minimum and the mean WIS for linear wetlands reflect a community that is more adapted to drier conditions than those found in depressional wetland locations.

Plant community composition data indicate that the influencing factor for biomass production may be more linked to species characteristics than community characteristics in that a few large species or species with extensive cover may dominate the biomass productivity of a site. For example, linear locations support a plant community dominated by *Equisetem arvense (EQAR),* while the remaining species in the community occur in smaller and similar cover percentages and frequencies. However, depressional locations support a plant community dominated primarily by *E. arvense* and *Calamagrostis canadensis (CACA).* Since the presence of *E. arvense* is similar in frequency and cover for both linear and depressional locations, we theorize that *C. canadensis* is the influential factor affecting differences in biomass values between wetland types. *C. canadensis* is a species that produces robust stands of high stature plants, and is described as a rhizomatous, erect grass reaching 1.5m at maturity (USDA 2008).

The similarities in the plant community between linear and depressional locations include both dominant and non-dominant species. The connectedness of the sites may contribute to similarities in community composition, particularly when it is possible for seed stock to be carried via flow from a linear site to a depressional site and so forth through the drainage.

In terms of ecosystem function, the development of a species list is assumed to be the cheapest and most useful approach for answering questions about a site's function and conditions (Slobodkin et al. 1980). This statement illustrates that the correct identification of wetland plants can provide insight from other research about the conditions of the site. For instance, two species common to both linear and depressional locations are known to be sensitive to sedimentation conditions (EQAR) and human disturbance (CACA) (Cronk and Fennessy 2001). Gage and Cooper (2007) associate these species with low surface water salinity and stable or fluctuating water tables.

Soil: Mean redox values in both linear and depressional were primarily in the moderately reduced state (Sparks 2003), but consistently highly variable. The variability of redox values in both wetland types is illustrated by standard deviations approaching the mean in both wetland types. Similarly variable redox values and presence of both reduced and oxidized conditions have been noted in montane riparian meadows (Dwire et al. 2004).

Mean soil pH was similar between linear and depressional locations, with values in the moderately acidic category. Other studies have shown intermediate and transitional rich fens as the primary wetland types with substrates in the moderately acidic range (Windell et al. 1986). Conifers are known to intensify soil acidity (Brady 1990), so the dominant conifer overstory found in the area may be the primary driver of soil pH. Alternately, the pH of soils can be influenced by soil redox with oxidation processes associated with a lower (more acidic) pH (Richardson and Vepraskas 2001).

TOC of wetland soils helps to define differences between mineral and organic soil types, with <12% considered mineral and >18% (Richardson and Vepraskas 2001) or >20% (Mitsch and Gosselink 1993) considered organic. Soils with TOC values between these upper and lower cut offs are considered mucky mineral, an uncommon but important subset of mineral substrates (Richardson and Vepraskas 2001). For comparison between linear and depressional wetlands, mean TOC at 10 cm depth in linear locations was mucky mineral, while mean TOC at 10 cm for depressional locations was either mucky mineral or organic. Mean TOC at 20 cm depth for linear and depressional were considered mineral soil.

Significant differences in soil parameters between linear and depressional wetlands exist in both physical characteristics (moisture, texture) and chemical characteristics (TOC). Soil moisture is most often the result of water table activity, and therefore wetlands have soil moisture content above that of upland soils where water table activity is further below the surface and less influential (Mitsch and Gosselink 1993). Depressional locations had water table activity at shallower depths than in linear locations, possibly explaining the differences in soil moisture between these types.

Significantly different proportions of clay and sand in linear and depressional sites are perhaps a response to the activity of surface flows. The influence of varying slopes of the study sites on local water velocities may have the most influence on flow velocities. As explained by Lane's (1955) bedload grain size and slope relationship, a decrease in slope is accompanied by a decrease in diameter of grain size. Specifically, depressional wetlands in this study are characterized as wide basin-like features with low gradient topography. Because clay particles are very small, they drop out of suspension and accumulate in low gradient slopes, where water velocities are very low, thus resulting in greater quantities of clay in depressional locations at both 10 and 20 cm depths. Larger sand particles alternately drop out of suspension and accumulate in areas with higher slope values, the fines continuing in suspension, thus resulting in greater quantities of sand in linear locations at both 10 and 20 cm depths. Silt, as an intermediate sized-particle, will drop out of suspension and accumulate in moderate sloped areas where water velocities are similarly moderate.

The other significantly different parameter (TOC) may be attributable to the linked relationship between moisture, TOC, and texture. Specifically, soil particle size (texture) is inversely related to TOC. Coarser soils such as sandy loams contain less TOC (Brady 1990), conditions that are similar in the linear locations of this study. Additionally, TOC improves water-holding capacity, which results in increased soil moisture values (Sparks 2003), conditions that are similar to the depressional locations.

Water: Mean well temperature values were higher in shallow wells than in deep wells for both wetland types. This is likely a result of conduction of air temperature to the surface layers of the soil, and subsequently to the water in the soil. Soils with high moisture contents have decreased resistance to the conductance transfer as compared to soils with low moisture (Brady 1990), and therefore water near the soil surface tends to stabilize to the temperature of the air (Jones and Mulholland 2000). Since the sampling of well temperatures completed mid day, it is expected that shallow well temperatures would be greater than deep well temperatures.

Differences in well water temperatures between wetland type during June and July may be attributable the slope values of depressional locations. The lower slope values at these locations may increase the residence time of water table flows allowing for greater influence of conductance in both shallow and deep wells. August temperatures may be similar due to climatic influence. During a period of cooler temperatures, a total of 1.1 inches (2.8 cm) of precipitation fell during four of the first six days of August (NRCS 2008a). This event may have increased or resumed the flow of cool water in depressional locations, thereby resulting in temperatures similar to linear locations.

We suspect well SC values may frequently be attributed to streamflow, particularly considering range of values and seasonal variation. Mean values of well SC at wetland locations are always within 50 µS/cm of the mean values of creek SC (Table 3). Mean well water SC during July was highest for both well types in linear and depressional locations. Assuming there is a connection between stream and well water, this may be attributable to the more concentrated state of solutes in suspension during the low flow period of July, likely driven by reduced quantity of surface and subsurface flows. Well SC values in this study are comparable to surface water SC recorded by Covino (2005) in a small order stream of southwest Montana, and surface waters recorded by Nicholson (1995) in Canadian swamp wetlands and moderate rich fens. Covino (2005) also noted a similar trend with increased SC during base (low) flow conditions as well as decreased SC following rain events. Well SC values are also comparable to surface waters of the Upper Columbia River Basin, and far below the standards for surface water quality for Montana (Lambing and Cleasby 2006).

One of the basic requirements for defining a wetland is a presence of saturated conditions during a portion of the year (Laboratory 1987). The mean values of shallow and deep wells for both wetland types are all within 32 cm of the surface, thus meeting the requirement for wetland definition. Similarly, the tendency for both linear and depressional wetlands to exhibit persistence of shallow water for a portion of the growing season also qualifies these areas as wetlands. The pattern of seasonal water level fluctuation for linear and depressional sites resembles those found in a study of subalpine wetlands in Italy, where late summer water depth during a normal precipitation year was recorded greater than 15 cm below early summer levels (Koch et al. 2007).

The persistence of shallow water is important to wetland plant growth and survival because period and length of inundation are critical conditions for plant maintenance (Mitsch and Gosselink 1993, Batzer and Sharitz 2006). The general temporal distribution of persistence of shallow water in deeps wells indicates that depressional locations maintain saturated conditions more than linear locations, as noted by percentage of wells with water at or above 30cm. The general temporal distribution of persistence of shallow water in depressional shallow wells is about similar to that of linear shallow wells. However, the lack of data showing shallow wells with water within

30 cm of surface for more than 60-70 days in either linear or depressional types is probably a result of the delayed installation of additional shallow wells. The total sampling days available for record were therefore limited.

While persistence of shallow water provides insight on length of saturation, water table data provide insight on the timing of the period of saturation. Many linear locations likely did not support saturated conditions in July, August, and September, periods when mean deep well data approached or exceeded depths of 30 cm. During this same time in depressional locations, even the lowest bar of the 95% confidence interval for deep well data is only slightly lower than 30 cm.

The influence of clay in wetland soils was examined by comparing water depth in shallow and deep wells within the wetland types, to address the theory that a perched water table results from the presence of the clay layer. Significantly different depths were evidenced sporadically, and during different, but overlapping, periods in linear and depressional locations. In linear locations, the significant differences between shallow and deep well levels occurred mid and late summer, while significant differences in depressional locations occurred early and mid summer.

Conclusive determination of the effect of the clay layer is difficult to identify in this study because significant differences were not noted consistently, particularly in depressional locations with measured high clay content. However, studies on Rocky Mountain wet meadows note that a perched water table can result from a subsurface clay layer, influencing length of saturation (Wilson 1969). Similar conditions were noted in fen wetlands of Minnesota, where surface spring activity results in shallow groundwater on top of an impervious layer, considered a separate hydrologic component than that of deep groundwater (Komor 1994). Additionally, Jones and Mullholland (2000) note a similar hydrologic regime of perched aquifer riparian zones of headwater streams (Figure 19).

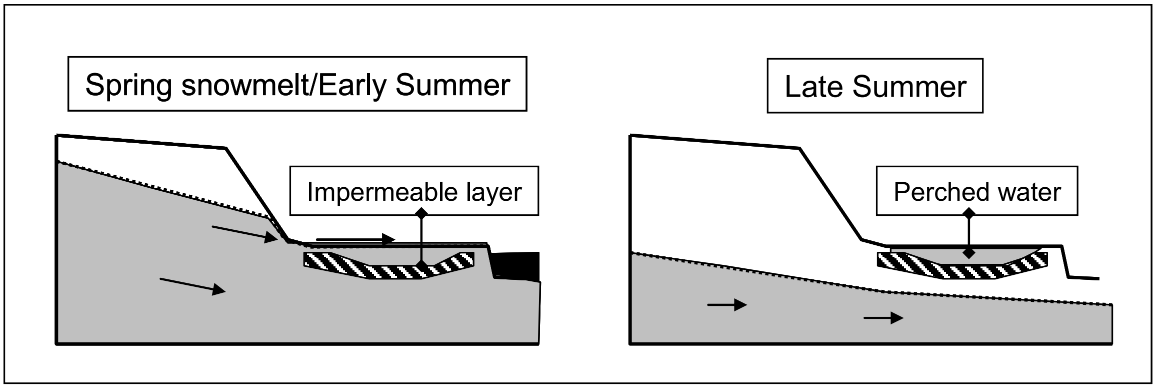

Figure 19: Hydrologic regime of perched aquifer riparian zone of headwater streams, modified from Jones and Mullholland (2000).

The presence of an impervious clay layer in subalpine wetlands may also be affecting the behavior of deep water tables, influencing the measurable water depth in deep wells. As was noted by Komor (1994), the subsurface clay layer confines the groundwater resulting in head pressure on the deep water table. In our study, it is plausible that deep wells, particularly in depressional locations where clay content is high, are behaving as piezometers. Deep wells may be recording piezometric head rather than true depth to water table. Our research noted sporadic periods when deep wells measurements were significantly different than shallow wells; however July was significantly different in both linear and depressional locations. July may be the period when piezometric head is at the lowest level of the season, due to decreased water table activity during periods of warm air temperatures and low precipitation.

The possibility that deep wells are recording piezometric head does not necessarily indicate that the deep well measurements are providing false information on the saturation conditions within the wetland. As noted by Komor (1994), the deep water table can upwell to the surface in areas where it is not confined by the impervious layer, implying that fissures through the impervious layer or veins of non-clay substrate can provide an outlet for the deep well water table to saturate surface soils.

Examination of Environmental Drivers

Data used for characterizing and comparing natural conditions also provide critical baseline information to investigate the relationships of environmental characteristics that influence the function of wetlands. This section examines the environmental drivers of wetland locations and the response of functional characteristics of vegetation and soil parameters, primarily redox, for subalpine wetlands.

Many ecological studies examine parameters that are linked in some way to other parameters, and as a consequence, indicate similar relationships in analysis. In this study, such relationships exist between parameters such as species richness and diversity and water level and soil moisture. However, there are many possible external factors that may affect these parameters, and therefore, the environmental drivers analysis in this study does not exclude variables based on potential co-variance.

The ecological and biogeochemical functions of wetlands are examined through vegetation and redox metrics. Vegetation parameters include cover, richness, diversity, wetland indicator score, and herb and wood biomass. Soil parameters include redox at 10 and 20 cm depth for the periods of July, August and September.

Examination of Multiple Drivers

Data for linear and depressional wetlands were combined for DCA. The results of DCA illustrate the differences between the locations based on vegetation composition data (Axis 1 and 2, Figure 20). The DCA axes are shown with those environmental parameters that are significantly correlated with axes values (Appendix B).

Clusters that included mostly linear and depressional locations are marked by the circles on Figure 19, illustrating that the primary distinction between the wetland types relates mostly to axis 1 values. The primary environmental drivers correlated with axis 1 values are depth to shallow water table throughout summer, as well as groundwater temperature throughout summer. The environmental drivers that correlate with the axis 2 values illustrate that the locations sort to a lesser extent by decreased soil sand content at 10-20 cm depth, and depth to shallow water table during late summer. The axis 2 values show that linear sites occur in a more narrow range of shallow water table depth in late summer and soil sand content at the 10-20 cm depth.

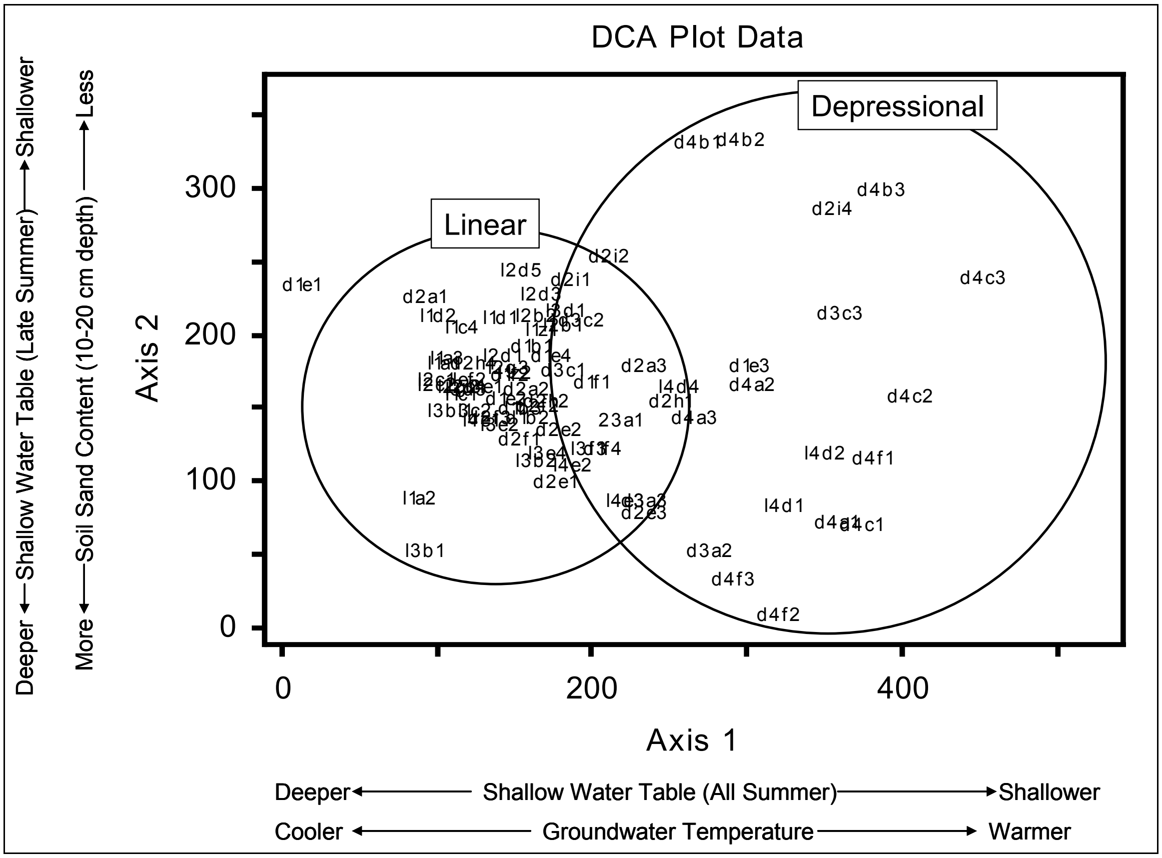

Figure 20: Diagram of DCA plot data and environmental parameters highly correlated with each axis. Symbols indicate locations, with first letter indicating linear "l" or depressional "d" wetland type.

Environmental Drivers by Wetland Type

Data stratified by wetland type were employed to examine the environmental drivers of wetland vegetation and redox parameters. Analysis included correlation and multiple regression. Dependent variables in the correlations included 10 vegetation response variables, 6 redox response variables, while independent variables were 18 soil parameters, and 24 water parameters. Selected parameters were included in the multiple regression to ensure n ≥ 12 (shallow well and soil texture data were excluded because of the limited number of locations with complete data sets for these variables). Here we address the hypothesis that functions (i.e., vegetation and redox) of the two subalpine wetland types are influenced by different environmental factors, and seek to identify those factors that are most influential.

Linear Location Vegetation. Correlations indicate that vegetation variables of linear locations were found to be significantly related to chemical and physical properties of the soil, as well as water table depth, temperature, and persistence of saturation. Multiple regression indicate significant relationships with water and soil chemistry parameters.

Correlation values resulting from both Pearson's and Spearman's methods can be found in Appendix B. Significant correlation coefficients between vegetation response variables and soil parameters (environmental drivers) for linear locations are presented in Table 10. Five vegetation response variables had significant relationships with two or more of 11 soil parameters. Vegetation cover is correlated with August soil pH at both depths, September 10 cm soil pH, and soil moisture at 10 cm. WIS is correlated with both 10 and 20 cm TOC. Richness is correlated with sand and clay content at 20 cm. SDI and herb biomass are correlated with 20 cm clay and silt content, respectively, and both are correlated with 10 cm TOC.

Table 10: Correlation coefficient (r) for significant relationships between soil environmental drivers and vegetation response variables for linear locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Vegetation Response Variables				
Soil Environmental Drivers	**Vegetation Cover**	**WIS**	**Richness**	**SDI**	**Herb Biomass**
August pH 10 cm	-.404(*)				
August pH 20 cm	-.483(*)				
September pH 10 cm	-.486(*)				
Moisture July 10 cm	-.649(**)				
Moisture August 10 cm	-492(**)				
nlog TOC 10 cm		.414(*)		.430(*)	-.436(*)
TOC 20 cm		.518(**)			
Silt Content 10 cm					.606(*)
Sand Content 20 cm			-.557(**)		
Silt Content 20 cm					.560(**)
Clay Content 20 cm			.615(**)	.540(*)	

Table 11 provides the significant correlation coefficients between vegetation response variables and water environmental drivers. Seven vegetation variables had significant relationships with one or more of 10 water parameters for linear locations. Vegetation and moss cover is correlated with August shallow and deep well temperatures, respectively. WIS is correlated with deep well water depths and persistence, and June deep well temperature. Species richness is correlated with July deep well depth and deep well persistence, while SDI is correlated with these same two independent variables plus deep well depth in early August and mid September. Herb and wood biomass are correlated with deep well depth in early August, whereas herb biomass is also correlated with deep well temperatures throughout the season and wood biomass is correlated with shallow well depth in September.

Table 11: Correlation coefficient (r) for significant relationships between water environmental drivers and vegetation response variables for linear locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Vegetation Response Variables						
Water Environmental Drivers	**Vegetation Cover**	**Moss Cover**	**WIS**	**Richness**	**SDI**	**Herb Biomass**	**Wood Biomass**
Deep well mid July			-.590(**)	-.409(*)	-.589(**)		
Deep well early Aug			-.529(**)		-.450(*)	.476(*)	.541(*)
Shallow early Aug							.695(*)
Deep well mid Sept					-.383(*)		
Shallow well mid Sept							.887(*)
Temp deep well June			-.390(*)			.417(*)	
Temp deep well July						.718(*)	
Temp deep well Aug		-.477(*)				.566(*)	
Temp shallow well Aug	.644(*)						
Deep well persistence			-.455(*)	-.413(*)	-.460(*)		

Table 12 provides the significant multiple regression formulas for vegetation response variables. Three vegetation variables were found to be significantly related to a combined suite of soil and/or water parameters for linear locations. 96% of the variability of bare ground is explained by the variability of deep well SC, soil moisture and pH. 52% of the variability of vegetation cover and 60% of the variability of native vegetation cover is explained by the variability of July soil moisture readings at both 10 and 20 cm depths.

Table 12: Multiple linear regression relationships from stepwise analysis between vegetation response variables and environmental drivers for linear locations. P to enter 0.05, P to exit 0.05.

Linear Vegetation Response Variable	**Equation**	**n**	**R^2**	**p ≤**
nLog Bare Ground	= -17.8247 – 0.01381 Water SC Deep Well (August) + 0.14632 Soil Moisture 20 cm (August) + 2.49125 nLog Water SC Deep Well (June) + 0.63639 Soil pH 10 cm (September)	12	0.9596	0.0000
Native Vegetation Cover	= 97.6479 – 0.88508 Soil Moisture 10 cm (July) + 0.68644 Soil Moisture 20 cm (July)	16	0.5166	0.0252
Vegetation Cover	= 99.4255 – 1.00152 Soil Moisture 10 cm (July) + 0.81733 Soil Moisture 20 cm (July)	15	0.5999	0.0116

Depressional Location Vegetation: Correlation analyses show that vegetation response variables of depressional locations are significantly correlated to the chemical properties of the soil, as well as water table depth, SC, temperature, and persistence of saturation. Multiple regression indicate relationships with water depth, persistence, SC, and soil chemistry.

Correlation values resulting from both Pearson's and Spearman's methods can be found in Appendix B. Table 13 provides the significant correlation coefficients between vegetation response variables and soil environmental drivers for depressional locations. Three vegetation variables had significant relationships with one or more of 4 soil parameters but no two vegetation variables were significantly correlated with the same soil parameter. WIS is correlated with soil moisture at 20 cm in July and August. Non native vegetation cover is correlated with July pH at 20 cm while wood biomass is correlated with august moisture at 10 cm.

Table 13: Correlation coefficient (r) for selected significant relationships between soil environmental drivers and vegetation response variables for depressional locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Vegetation Response Variable		
Soil Environmental Driver	**WIS**	**Non Native Vegetation Cover**	**Wood Biomass**
July pH 20 cm		-.760(**)	
Moisture July 20 cm	-.352(*)		
Moisture August 10 cm			.327(*)
Moisture August 20 cm	-.400(*)		

Table 14 provides the significant correlation coefficients between vegetation response variables and water environmental drivers. Four vegetation variables had significant relationships with one or more of 15 water parameters for depressional locations. Of the vegetation variables, herb biomass was significantly correlated with most of the water parameters whereas the other three vegetation variables were correlated with only one to four of the 15 water parameters. Of the remaining variables, bare ground is correlated with shallow and deep well persistence and depth in September. Wood biomass is correlated with deep well depth in July deep well SC in June. WIS is correlated with a single environmental driver, deep well depth in June.

Table 14: Correlation coefficient (r) for selected significant relationships between water environmental drivers and vegetation response variables for depressional locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Vegetation Response Variable			
Water Environmental Driver	**Bare Ground Cover**	**Wetland Indicator Score**	**Herb Biomass**	**Wood Biomass**
Deep Well Early June		-.390(*)	.515(**)	
Deep Well Late June			.382(*)	
Deep Well Mid July			.415(*)	-.786(*)
Shallow Well Mid July			.582(**)	
Deep Well Early August			.498(**)	
Shallow Well Early August			.477(*)	
Deep Well Mid September	.435(*)			
Shallow Well Mid September	.451(*)		.392(*)	
LogN of SC Deep Well June				.802(*)
Temperature Deep Well July			.397(*)	
Temperature Shallow Well July			.524(*)	
SC Deep Well July			.541(**)	
SC Deep Well August			.393(*)	
Deep wells persistence	.358(*)			
Shallow wells persistence	.404(*)		.343(*)	

Table 15 provides the significant multiple regression formulas for vegetation variables for depressional locations. Three vegetation variables were found to be significantly related to a combined suite of soil and/or water parameters. 97% of the variability of species richness is explained by the variability of deep and shallow water depth, deep well persistence, deep well SC, as well as soil moisture, pH and TOC. 63% of the variability of SDI and 93% of the variability of WIS are explained by the variability of deep well water depth and soil moisture.

Table 15: Multiple linear regression relationships from stepwise analysis between vegetation response variables and environmental drivers for depressional locations. P to enter 0.05, P to exit 0.05.

Vegetation Response Variable	Equation	n	R^2	p ≤
Species Richness	= 43.6429- 0.42157 Shallow Well Water Depth (September) – 0.34570 Deep Well Water Depth (late June) – 0.13212 Soil Moisture 10 cm (July) + 0.12543 # Days water depth within 30 cm of surface (Deep wells) – 1.52939 nLog Soil TOC (20 cm) – 5.79662 Soil pH 20 cm (September)- 0.02046 SC Deep Well (August)	16	0.9693	0.0080
SDI	= 2.97397 – 0.04809 Deep Well Water Depth (early June) – 0.01647 Soil Moisture 10 cm (July)	16	0.6304	0.0044
WIS	= 4.49800 + 0.04924 Deep Well Water Depth (August) – 0.09010 Deep Well Water Depth (Early June) – 0.03301 Soil Moisture 10 cm (August)	16	0.9258	0.0000

Linear Location Redox: Correlations indicate that redox parameters of linear locations were found to be significantly related to chemical and physical properties of the soil, as well as water table depth, SC, temperature, and persistence of saturation. Multiple regression indicate a single relationship with water chemistry.

Correlation values resulting from both Pearson's and Spearman's methods can be found in Appendix B. Table 15 provides the significant correlation coefficients between soil redox response variables and soil environmental drivers for linear locations. All six of the redox variables had significant relationships with exactly 2 of the 4 soil parameters. Of these, soil moisture at 10 cm in August was correlated with the most redox variables.

Table 16: Correlation coefficient (r) for selected significant relationships between soil environmental drivers and soil response variables for linear locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Redox Response Variables					
Soil Environmental Drivers	**July Redox 10 cm**	**July Redox 20 cm**	**August Redox 10 cm**	**August Redox 20 cm**	**Sept Redox 10 cm**	**Sept Redox 20 cm**
Moisture August 10 cm	-.408(*)	-.493(**)		-.423(*)	-.412(*)	-.527(**)
Moisture August 20 cm					-.397(*)	-.468(*)
nlog TOC 10 cm	.477(*)		.393(*)			
Clay 10 cm		.587(*)	.621(*)	.677(*)		

Table 17 provides the significant correlation coefficients between redox response variables and water environmental drivers for linear locations. All 6 of the redox parameters had significant relationships with one or more of 11 water parameters. Deep well water depths were correlated with 4 of the redox variables. Shallow well water depths were correlated with 4 of the redox variables. Shallow well SC was correlated with 2 variables, while deep well SC was correlated with 1. Shallow temperature and deep temperature were each correlated with 1 variable. Deep well persistence was also correlated with 1 variable.

Table 17: Correlation coefficient (r) for significant relationships between water environmental drivers and soil response variables for linear locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Redox Response Variables					
Water Environmental Drivers	**July Redox 10 cm**	**July Redox 20 cm**	**August Redox 10 cm**	**August Redox 20 cm**	**Sept Redox 10 cm**	**Sept Redox 20 cm**
Deep well early June	-.389(*)					
Deep well late June	-.438(*)	-.448(*)				
Deep well mid July	-.429(*)	-.412(*)	-.551(**)	-.483(*)		
Shallow well mid July		-.767(*)	-.668(*)		-.709(*)	-.733(*)
Deep well early Aug		-.402(*)	-.448(*)			
Deep well mid Sept		-.419(*)	-.468(*)			
SC shallow well June			-.960(*)	-.976(*)		
Temp shallow well July	-.759(*)					
SC deep well July						-.410(*)
Temp deep well Aug	-.472(*)					
Deep well persistence	-.440(*)					

Table 18 provides the single significant multiple regression formulas found to be significantly related to a combined suite of soil and/or water parameters for linear locations. 58% of the variability of September redox at 10 cm is explained by the variability of deep well SC in July and August.

Table 18: Multiple linear regression relationships from stepwise analysis between redox response variables and environmental drivers for linear locations. P to enter 0.05, P to exit 0.05.

Redox Response Variable	**Equation**	**n**	**R^2**	**p ≤**
Redox September 10 cm	= 275.858 – 1.00409 Water SC Deep Well (August) + 0.60325 Water SC Deep Well (July)	14	0.5846	0.0441

<u>Depressional Location Redox:</u> Correlations indicate that redox parameters of depressional locations were found to be significantly related to chemical and physical

properties of the soil, as well as water table depth, SC, temperature, and persistence of saturation. Multiple regressions indicate significant relationships with water depth, temperature, SC, and soil chemistry.

Correlation values resulting from both Pearson's and Spearman's methods can be found in Appendix B. Table 19 provides the significant correlation coefficients between soil redox response variables and soil environmental drivers for depressional locations. Five redox variables had significant relationships with two or more of 6 soil parameters. Soil moisture at 10 cm was correlated with 5 redox variables, while soil moisture at 20 cm was correlated with 3 redox variables. TOC and silt content were each correlated with 1 redox variable.

Table 19: Correlation coefficient (r) for selected significant relationships between soil environmental drivers and soil response variables for depressional locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Redox Response Variables					
Soil Environmental Drivers	**July Redox 10 cm**	**July Redox 20 cm**	**August Redox 10 cm**	**August Redox 20 cm**	**Sept Redox 10 cm**	**Sept Redox 20 cm**
Moisture July 10 cm	-.491(**)	-.505(**)	-.459(**)	-.590(**)		-.387(*)
Moisture July 20 cm		-.523(**)	-.384(*)	-.545(**)		
Moisture August 10 cm	-.417(**)	-.555(**)	-.554(**)	-.780(**)		-.395(*)
Moisture August 20 cm		-.394(*)	-.382(*)	-.569(**)		
LogN of TOC 20 cm				-.404(**)		
Silt content 10 cm						.977(*)

Table 20 provides the significant correlation coefficients between redox response variables and water environmental drivers for depressional locations. All 6 of the redox parameters had significant relationships with one or more of 16 water parameters. Deep well water depths were correlated with all of the redox variables. Shallow well water depths were correlated with 5 of the redox variables. All of the correlations between redox variables and well depth variables were negative, indicating that redox values increase when well depth decreases. Deep well temperature was correlated with 2 redox variables, shallow well temperature was correlated with one, and well SC was correlated with four. Deep and shallow well persistence were correlated with 5 and 6 variables, respectively.

Table 20: Correlation coefficient (r) for selected significant relationships between soil environmental drivers and soil response variables for depressional locations. ** indicates significant relationships at the 0.01 level, * indicates significant relationships at the 0.05 level.

	Redox Response Variables					
Water Environmental Drivers	**July Redox 10 cm**	**July Redox 20 cm**	**August Redox 10 cm**	**August Redox 20 cm**	**Sept Redox 10 cm**	**Sept Redox 20 cm**
Deep Well Early June	-.438(**)	-.358(*)	-.364(*)			-.372(*)
Deep Well Late June	-.416(*)					
Deep Well Mid July	-.689(**)	-.662(**)	-.680(**)	-.796(**)	-.624(**)	-.475(**)
Shallow Well Mid July	-.777(**)	-.575(**)	-.507(*)	-.454(*)	-.567(**)	
Deep Well Early August	-.684(**)	-.643(**)	-.678(**)	-.654(**)	-.557(**)	-.435(**)
Shallow Well Early August	-.689(**)	-.648(**)	-.691(**)	-.703(**)	-.556(**)	
Deep Well Mid September	-.692(**)	-.695(**)	-.660(**)	-.622(**)	-.593(**)	-.358(*)
Shallow Well Mid September	-.414(*)	-.426(*)	-.512(**)	-0.307	-.475(*)	
Temperature Deep Well July	-.437(**)	-.373(*)				
Temperature Shallow Well July	-.641(**)					
SC Deep Well July						-.386(*)
SC Shallow Well July			-.482(*)		-.784(**)	
SC Deep Well August			-.543(**)	-.473(**)	-.486(**)	
SC Shallow Well August			-.447(*)	-.365(*)	-.487(**)	-.421(*)
Deep well persistence	-.558(**)	-.465(**)	-.493(**)	-.380(*)	-.375(*)	
Shallow well persistence	-.591(**)	-.450(**)	-.547(**)	-.495(**)	-.503(**)	-.402(*)

Table 21 provides the significant multiple regression formulas for all 6 redox variables found to be significantly related to a combined suite of soil and/or water parameters for depressional locations. 63% of the variability of July redox at 10 cm and 99% of the variability of July redox at 20 cm is explained by the variability of deep well water depth and shallow well water temperature, with soil moisture also significant for July redox at 20 cm. 95% of the variability of August redox at 10 cm is explained by the variability of deep well water depth and soil moisture. 100% of the variability of August redox at 20 cm is explained by the variability of shallow and deep well water depth, temperature, and SC, as well as soil moisture and TOC. 98% of the variability of September redox at 10 cm is explained by the variability of shallow well water depth, deep well water temperature, deep and shallow well SC, and soil moisture. 53% of the variability of September redox at 20 cm is explained by the variability of deep well water depth and soil moisture.

Table 21: Multiple linear regression relationships from stepwise analysis between redox response variables and environmental drivers for depressional locations. P to enter 0.05, P to exit 0.05.

Depressional Redox Response Variable	Equation	n	R^2	p ≤
Redox July 10 cm	= 711.812 – 5.57353 Deep Well Water Depth (September) – 47.3204 Water Temperature Shallow Wells (July)	16	0.6314	0.0056
Redox July 20 cm	= 943.740 – 6.82332 Deep Well Water Depth (September) – 2.44520 Soil Moisture 20 cm (August) – 70.4966 Water Temperature Deep Wells (August)	16	0.7945	0.0021
Redox August 10 cm	= -11.7849 – 11.7849 Deep Well Water Depth (September) - 8.23349 Soil Moisture 10 cm (July) + 4.51781 Soil Moisture 20 cm (July)	16	0.9461	0.0006
Redox August 20 cm	= 95.0635 + 2.24674 Shallow Well Water Depth (September) – 9.72375 Deep Well Water Depth (September) – 7.01142 Soil Moisture 20 cm (August) – 33.2166 Deep Well Water Temperature (July) + 117.377 nLog Soil TOC (20 cm) – 0.10490 Water SC Deep Well (July) – 0.08180 Water SC Shallow Well (August) + 38.6319 Water Temperature Shallow Well (July)	16	0.9989	0.0000
Redox September 10 cm	= -79.0883 – 4.63346 Shallow Well Water Depth (July) + 2.69993 Soil Moisture 10 cm (August) + 19.3529 Water Temperature Deep Well (August) + 15.3979 Water Temperature Deep Well (June) – 0.62412 Water SC Deep Well (August) – 1.00700 Water SC Shallow Well (July)	16	0.9763	0.0000
Redox September 20 cm	= 358.536 – 8.60212 Deep Well Water Depth (early June) – 4.91133 Soil Moisture 10 cm (July)	16	0.5305	0.0076

Discussion

Wetness is the primary characteristic and driver that distinguishes a wetland from the surrounding upland. Since this characteristic more than any other defines the existence of a wetland (Brinson 1993b), most functions of wetland and riparian areas are in some way linked to the many facets of hydrology (Gage and Cooper 2007). However, as pointed out by Brinson (1993b):

> *When single environmental factors such as wetness become the main focus for explaining changes in the functioning of wetlands, there is a tendency to overlook alternative sources of variation.*

Because wetlands are defined as a combination of hydric vegetation and soils, and saturated water conditions (Laboratory 1987), there exist many possible interrelationships among soil and water drivers that influence the function of a wetland.

In this study of small subalpine wetlands, we have found that many soil and water parameters are significantly related to the ecological and biogeochemical functions of a wetland. The metrics used to examine these functions are vegetation and redox parameters, what we've designated as response variables, of both linear and depressional wetland types. A few of these soil and water parameters appear to be most important in controlling wetland structure and function and their relative importance varies between the two categories of response variables.

Vegetation: The ecological functions of wetland vegetation that we examined include species biodiversity and richness, community composition, and primary productivity. Using DCA we have shown that the differences in community composition along Axis 1 and Axis 2 are related to water parameters, and soil and water parameters respectively. The majority of the sample locations sort by wetland type across Axis 1 with the gradient across this axis significantly related to shallow well data throughout the summer and groundwater temperature of deep wells, while sample locations sort primarily by species response across Axis 2 and are related to late season water depth and soil texture.

It is important to note the consistency of correlation between all the shallow well data and Axis 1 values (Figure 20). Although there are significant correlations between deep well data and Axis 1 values, they are only at the 0.05 significance level and only in June and August while the significant correlations between shallow well data and Axis 1 values are at the 0.05 significance level in late June and at a more significant level of 0.01 for all other times of the sample season. This implies that shallow well water tables play more of a role in influencing species composition of these wetlands, and to a certain extent the wetland type, than do water table levels in deep wells. This influence of depth to groundwater on plant assemblages has been shown in other studies, for example, riparian communities (Stomberg et al. 1996) and spring-oriented wetland communities (Patten et al. 2008).

Previous discussion on groundwater temperature linked the more gradual slope of depressional locations with increased residence time of subsurface flows, thus increasing the effect of heat conductance from the air through the soil (Brady 1990). The significant relationship between Axis 1 values and groundwater temperatures may also indicate a response of wetland plant species to these conditions. This is corroborated by the significant relations between water temperature and vegetation parameters in linear and depressional locations. Temperatures commonly influence biological functions and elevated surface water temperatures have been noted to influence a range of organismal communities, including vegetation, in a study of a Canadian riparian wetland by Taylor and Dykstra (2005).

We have speculated that a clay layer in the wetland sites may contribute to the presence of a perched water table recorded by shallow wells. In support of this, we found that there are periods when shallow water tables are significantly different than the deep well water table and that depressional locations, with significantly higher soil clay content and a clay layer usually found when well holes were augered, may particularly exhibit this condition. The results of DCA provide support for this theory in that the plant communities of depressional locations are distinct from many linear locations and are significantly related to shallow surface water depth.

While the DCA provides insight into significant vegetation/environmental relationships that help explain differences between linear and depressional locations, it also illustrates similarities in plant communities in that there is a notable overlap in linear and depressional wetland communities. This overlap is likely a consequence of the connectedness of the wetlands, where seed and propagules may be easily dispersed from linear to depressional locations which occur along a gradient within the same drainage. Middleton et al (2006) have shown this hydrologic connectedness of wetlands to be a primary influence to seed dispersal and biodiversity.

We have found that there are several soil parameters that are significantly related to both linear and depressional wetland types, and for each wetland type individually. Soil moisture, noted by others as a defining parameter wetland community structure and composition (Mitsch and Gosselink 1993, Castelli et al. 2000, McMaster and McMaster 2001), is a common parameter at 10 cm in August for both wetland types as it relates to two different vegetation response variables (i.e., vegetation cover and WIS). In addition to soil moisture, a significant soil parameter common to both wetland types is soil pH, which is similarly correlated to invasive vegetation in a wetland study by Herrick and Wolf (2005).

Soil parameters that are exclusively significant to linear locations include texture and TOC. Texture is a soil property that can influence the composition of plant communities (Brady 1990) and therefore, a plant community such as a wetland plant communities can indicate soil type (Johnston et al. 2007). Distinct plant communities are also associated with the accumulated organic matter and high TOC of peatlands, with certain species found in this wetland type only (Mitsch and Gosselink 1993). TOC is also noted to be significantly related to distinct communities, particularly *Sphagnum*, in mountain wetlands of Kentucky (Thompson et al. 2007b).

McMaster and McMaster (2001) recognize the importance of certain soil conditions as significant for wetland vegetation, however, they place greater emphasis on the dynamic hydrological conditions that influence wetland vegetation. Our study has examined components of the hydrological conditions, in the form of shallow and deep well depths throughout summer and persistence of saturation, and found both having significant correlations with response variables of vegetation and redox at linear and depressional locations. Dwire et al (2004) note distinct plant communities corresponding with depths to water table, including a positive correlation with water table depth and herb biomass and a negative correlation with water table depth and species richness. Both relationships are similar to those in our study. The model proposed by Patten et al (2008) links deeper water table depth with an increase in WIS, a relationship noted for both linear and depressional locations in our study. A number of our correlations also agree with the results of the DCA, where shallow water depth throughout the sampling season is shown to have a significant relationship with the plant communities of the sites.

Despite the fact that some environmental drivers are significantly correlated to vegetation response variables in both linear and depressional locations, multiple regressions indicate that linear and depressional locations have no shared environmental drivers for the same vegetation response variables. Additionally, many of the results of the multiple regressions show associations of independent parameters that are unexplainable in the context of this study, or show contradictory associations within a formula. An example of these contradictions includes WIS with a positive relationship with water depth in August and a negative relationship with soil moisture in August. Therefore, we are not confident about any conclusions made on the results of the multiple regressions.

Redox: In wetland soils, redox is known to control most of the important biogeochemical reactions in the soil. In particular, redox influences the availability of essential plant nutrients and is associated with maintenance of characteristic plant communities (Richardson and Vepraskas 2001). In our study, we considered all of the redox response variables as functions, at both 10 cm and 20 cm depths during July, August, and September. However, since redox data are highly variable and it is difficult to quantify the functional role of redox between the different sample dates, the following discussion addresses only the drivers of redox as a whole.

Both linear and depressional locations have two common soil parameters (moisture August 10 cm and 20 cm) significantly related to redox response variables. Soil texture and TOC also are significantly related to redox at linear and depressional locations. Both of these soil characteristics can influence soil moisture which, with an increase in soil saturation, is found to be negatively correlated with redox potential (more reduced conditions) (Kadlec and Knight 1996). TOC alone can influence redox when demand for oxygen by the microbial breakdown of the TOC results in reduced conditions (Kadlec and Knight 1996).

Linear and depressional locations have nine common water parameters significantly related to all of the redox response variables. These include shallow and deep well water depth, SC, temperature and shallow water persistence. Significant negative relationships with well depth are expected because surface saturation is more likely to correspond with lower redox potential (more reduced conditions) (Mitsch and Gosselink 1993). This basic relationship also explains the significant negative relationships with persistence, indicating that the greater period of saturation corresponds with lower redox potential.

SC and temperature values may actually be an inverse surrogate for the amount of dissolved oxygen in the water, conditions that are directly related to surface flow (Figure 21). SC is known to decrease with increased flows because of the lower solute concentrations (Hem 1985), and in the subalpine, temperature often decreases with increased flows from snowmelt and cool temperature precipitation events. Inversely, dissolved oxygen levels are likely to increase with these increased flows not only because moving water gains oxygen but because of the greater solubility of oxygen in cooler water (Lambing and Cleasby 2006) . The greater availability of dissolved oxygen would correspond with redox values in an oxidized (less reduced) state, a common condition found in natural wetlands (Kadlec and Knight 1996).

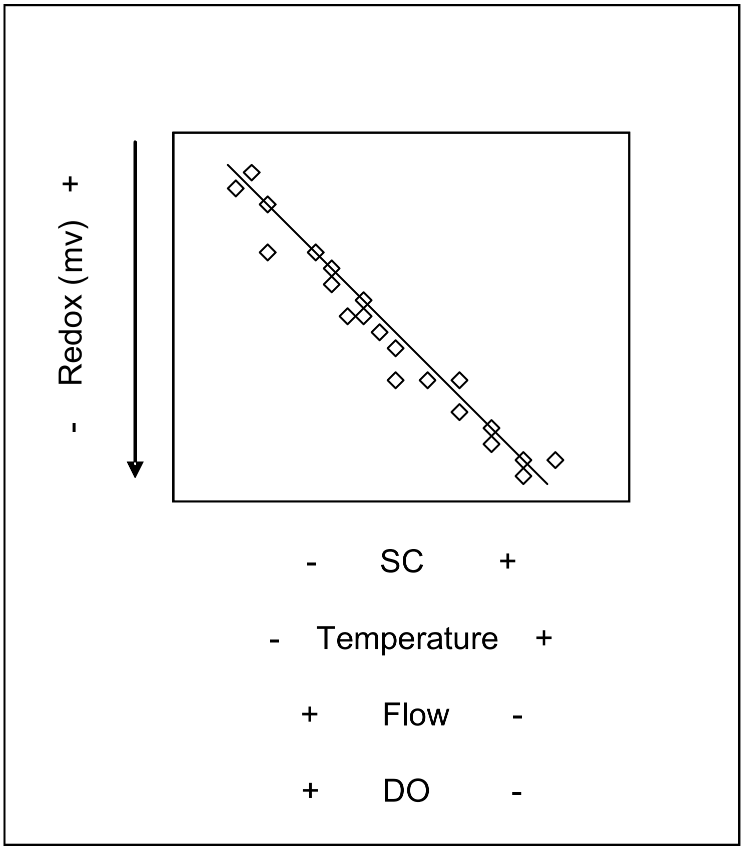

Figure 21: Conceptual relationship between redox and SC, temperature, DO, and flow.

Redox of wetland soils is known to be spatially and temporally variable, a response to variability of environmental drivers. For example, following a saturation event, Richardson and Vepraskas (2001) note a delay in the response by redox potential. This delay may explain the inconsistent timing of changes in environmental drivers and redox response noted in our study. For example, we note that at linear locations August moisture at 10 cm is not significantly correlated with linear August redox at 10 cm. Additionally, we theorize that if locations support saturated conditions during the driest time of the year (July and August), these locations are likely to support saturated conditions for the length of the growing season. This may explain why July well data in linear locations and July and August well data in depressional locations have the greatest number of significant relationships and are significantly related to redox values throughout the sampling season.

Comparison of Restored to Undisturbed Wetlands

Since much of the restoration of US wetlands has been completed in the past 30 under the mandates of section 404 of the Clean Water Act, the discipline of restoration science is a new and evolving realm of ecology. Consequently, the continued completion of wetland restoration projects under the jurisdiction of federal regulatory agencies garners much attention and critical examination of the science and success of restoration.

Presently, restoration success is determined by monitoring of vegetation, water, and soil conditions. However, studies indicate that the current definition of restoration success is often insufficient in addressing the complete replacement of wetland structure and function (National Research Council 1992). A key tool in addressing this issue is expanding upon the knowledge of natural conditions, to better understand the historic trajectory of undisturbed wetlands and gauge the success of restoration efforts.

> *"Restoration attempts to return an ecosystem to its historic trajectory… the general direction and boundaries of that trajectory can be established through a combination of knowledge of the damaged ecosystem's pre-existing structure, composition and functioning, studies on comparable intact ecosystems, information about regional environmental conditions, and analysis of other ecological, cultural and historical reference information." (SER 2004)*

Previous results and discussion sections provide insight on the historic trajectory for small subalpine wetlands of the northern Rocky Mountains. Characterization and comparisons of the two wetland types (linear and depressional) provide an examination of environmental conditions of undisturbed sites, while identification of environmental drivers explain the conditions that most directly influence the function of these wetlands. This section uses this baseline information for undisturbed wetlands to examine the response and success of restored sites.

In our study, the term restored refers to two types of wetlands; altered sites that have undergone restoration efforts and mitigation sites where efforts were aimed at creation of new wetland areas. The single term "restored" to describe both types of disturbance is used to simplify discussion regarding the sites.

Although both linear and depressional wetland types are represented in the restored sites, the small number of restored sites (n=11) does not provide enough data to make robust statistical conclusions about the condition of these locations. The data do, however, provide a glimpse at the range of variability seen in restored locations, as compared to undisturbed locations.

This section's comparisons of restored and undisturbed locations include examination of the relative values of parameters for restored locations compared to the range of variability of undisturbed locations. Those for restored locations may fall all, partially within, or outside the range of variability at undisturbed locations, or be absent entirely. There are only three sampling locations at the only restored depressional site, consequently, the distribution of data from these locations across the range of variability of undisturbed depressional sites is limited and may be clustered at some point along this scale, or dispersed along the scale, as might be those from one undisturbed depressional site.

Linear

The three linear wetlands which were influenced by restoration are located in two of the four drainages studied. Table 22 illustrates the relatively similar landscape characteristics among linear restored sites.

Table 22: Description of individual restored linear wetlands and their associated landscape characteristics

Wetland	Type	Condition	Elevation (m)	Slope (%)	Aspect (°)	Overstory (%)	Width (cm)
1Z	Linear	Restored	2281	20	13	19.25	720
2C	Linear	Restored	2304	9	287	18.5	308
2D	Linear	Restored	2298	10	283	15.75	790

Vegetation: Species frequency and mean cover are compared between linear restored locations and linear undisturbed locations in Table 23. Although the restored and undisturbed locations support different dominant and frequently occurring species, the communities of the two conditions are relatively similar. There are 16(of 20) common species between the two wetland conditions. Of these, there are 5 species (*Equisetum arvense, Geranium richardsonii, Senecio triangularis, Arnica mollis, and Aster foliaceus)* in the dominant community (all species as a group with frequency >50.0 and cover > 2.0).

Table 23: Frequently occurring species of linear restored and undisturbed locations. Species indicated by (*) are present in both conditions but are only frequently occurring (top 20 present species) in restored locations.

	Linear Undisturbed		Linear Restored	
Species	Frequency of Presence (%)	Mean Cover per Location (%)	Frequency of Presence (%)	Mean Cover per Location (%)
EQAR	100	14.9	100	9.531
GERI	93	5.4	75	4.656
SETR	93	5.8	75	8.406
MIPE	82	5.0	38	1.219
ARMO	79	3.3	63	2.375
ASFO	61	4.4	63	7.875
CACA	54	7.0	13	0.5625
CADI	50	1.330	50	3.000
GATR	50	1.268	63	2.594
FRVI	43	1.134	100	3.250
GLGR	43	1.223	50	0.750
STAM	43	1.973	38	1.281
THOC	43	1.696	38	2.625
EPCI	40	1.259	63	1.219
OSBE	40	0.598	63	0.438
PAFI	40	1.804		
ABBI	36	1.054		
MAST	36	1.250		
SAOC	36	4.929	38	1.531
TAOF	32	0.214	75	1.531
EUCO			63	2.000
ELGL*	14	0.071	50	1.156
PHPR*	4	0.008	50	1.344
DEEL*	4	0.017	38	0.375

Several parameters indicate that conditions at restored locations are comparable to conditions at undisturbed locations. Vegetation cover is a common metric used to determine restoration success, and we find that vegetation cover is similar between restored and undisturbed locations. Moss and bare ground cover are also similar between wetland conditions, potentially indicating appropriate conditions to support moss species and the minimal level of disturbance at the locations. Plant community parameters are similar as well, with species richness and SDI of restored locations being within the range of variability of undisturbed locations. These vegetation parameters with similar ranges between restored and undisturbed locations illustrate one aspect of success in the wetland restoration process.

Although the range of variability of non-native cover for restored locations is similar to that of undisturbed locations, the mean cover of noxious weeds is a concern for these restored locations. Figure 22 illustrates that while the mean cover of noxious weeds for both conditions is relatively low (0.06 restored, 0.009 undisturbed), restored locations support a higher mean cover of noxious weeds.

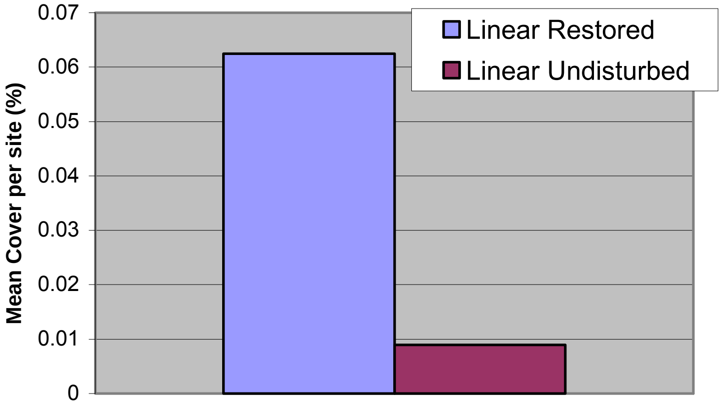

Figure 22: Mean noxious weed cover per location for undisturbed and restored linear wetlands.

WIS for restored linear locations, although within the range of variability of undisturbed locations, occur in the upper half of that range (Figure 23). Data for restored locations are recorded only above 2.3, indicating plant communities that are adapted to drier conditions. These WIS values are equivalent to communities that are in the FACW-/FAC+/FAC indicator status categories, with frequency of occurrence in wetlands ranging from 33%-66% to 67%-99% (Table 2).

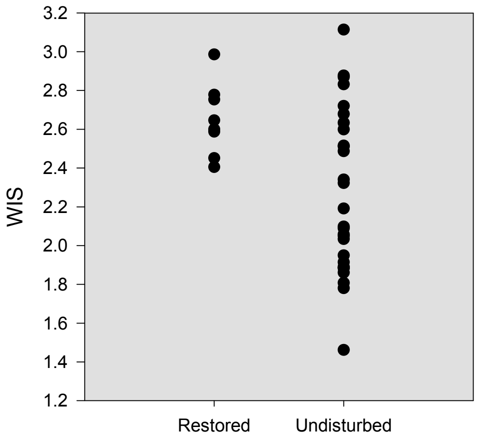

Figure 23: Wetland Indicator Score (WIS) for restored and undisturbed linear locations.

Wood biomass values for restored linear locations reflect the relative absence of woody plants in the restored locations (Figure 24). 1 of the 8 locations contained woody species, and the single recorded value was at the bottom of the normal range of variability for undisturbed locations. This implies that disturbance prior to or during restoration resulted in woody plants being removed or destroyed, leaving a community composed primarily of herbaceous plants.

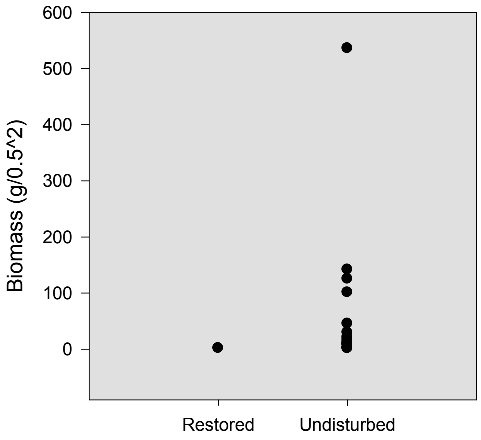

Figure 24: Wood Biomass for restored and undisturbed linear locations.

<u>Soil:</u> Several soil parameters of restored locations have a range similar to that of undisturbed locations. August redox at 10 cm and July, August, and September redox at 20 cm were similar between restored and undisturbed locations. Redox was highly variable for both conditions, likely resulting in similar ranges of variability. Soil pH at 10 and 20 cm for restored locations was consistently at the center of the range of variability of undisturbed locations. TOC and August soil moisture at 10 cm for restored locations were also at the center of range of variability of undisturbed locations, while TOC and August soil moisture at 20 cm had a cluster of lower centered values with isolated data points at the upper end of the undisturbed range. Soil texture in restored locations also had consistently similar ranges of variability to undisturbed locations for all particles at both 10 and 20 cm depths.

Soil parameters that had ranges of variability not evenly distributed across the range for undisturbed locations include July moisture, and July and September redox.

July soil moisture content at 10 and 20 cm are distributed in the lower portion of undisturbed location values, and reflect overall drier conditions at restored locations than undisturbed locations (Figure 25). Moisture content is below 51% at 10 cm and below 40% at 20 cm.

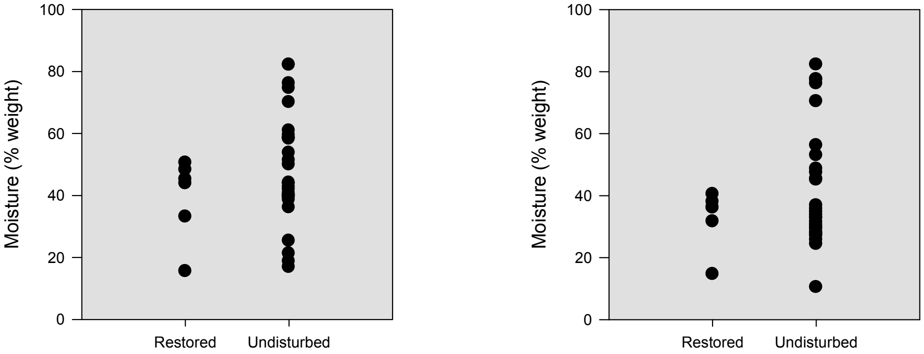

Figure 25: July soil moisture content at 10 cm (left) and 20 cm (right) for restored and undisturbed linear locations.

July and September redox at 10 cm are in the upper half of the distribution of undisturbed locations, and reflect more oxidized conditions in restored locations than undisturbed locations (Figure 26). These values mostly correspond with the moderately reduced (or facultative) redox category.

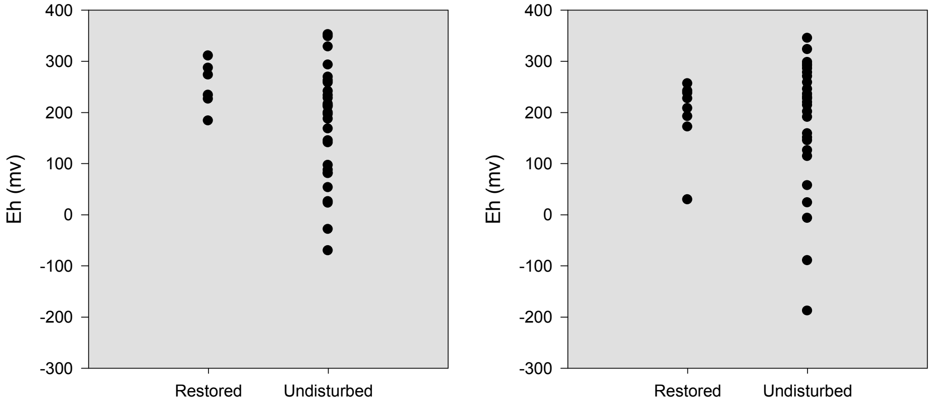

Figure 26: July (left) and September (right) soil redox at 10 cm for restored and undisturbed linear locations.

<u>Water:</u> The ranges of variability of several water parameters were similar in restored and undisturbed locations. Shallow well water table depths were similar throughout the year at restored and undisturbed locations, with distributions of values being nearly identical between conditions. Deep groundwater temperatures in July and August and shallow groundwater temperatures in August also exhibited nearly identical distributions between conditions, while deep groundwater temperatures in June and shallow groundwater temperatures in June and July for restored locations were clustered around center with isolated points above the upper data points of the range of variability for undisturbed locations. The range of variability for restored location groundwater SC throughout the sampling season fell across the range of variability for restored locations, although distributions for both shallow and deep wells were highly variable. The parameters with similar ranges of variability for restored and undisturbed locations

represent the majority of parameters recorded in this study and provide an additional useful suite of metrics to judge the success of restoration.

Deep well water table depths were within the range of variability for undisturbed locations in early summer, while late summer depths were within and below the range of variability for undisturbed locations. Deep well water table data for restored locations in early June and late June were distributed in the upper end of the range of variability of undisturbed locations, indicating water table activity near ground surface during the early part of summer (Figure 27).

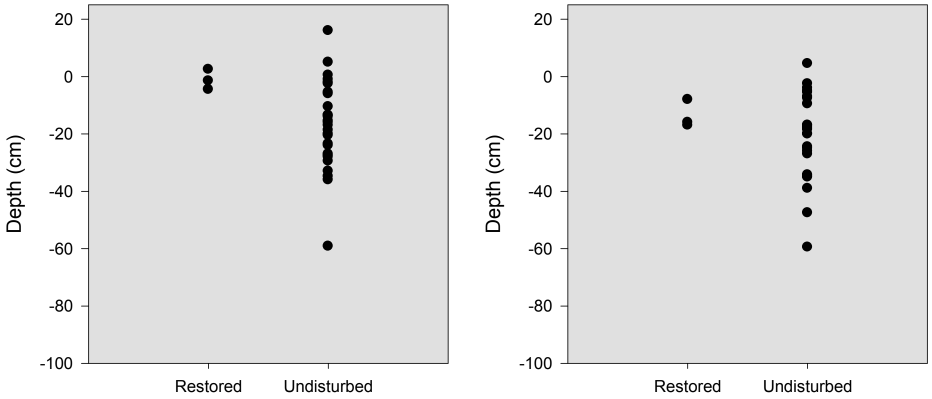

Figure 27: Depth to deep well water table in early June (left) and late June (right) for restored and undisturbed linear locations.

Alternately, deep well water table data for restored locations in July, August, and September were distributed at and below the lower distributions of undisturbed locations (Figure 28). This distribution also illustrates the change from near surface water table activity in the early summer to subsurface water table activity in mid summer of deep wells in restored locations.

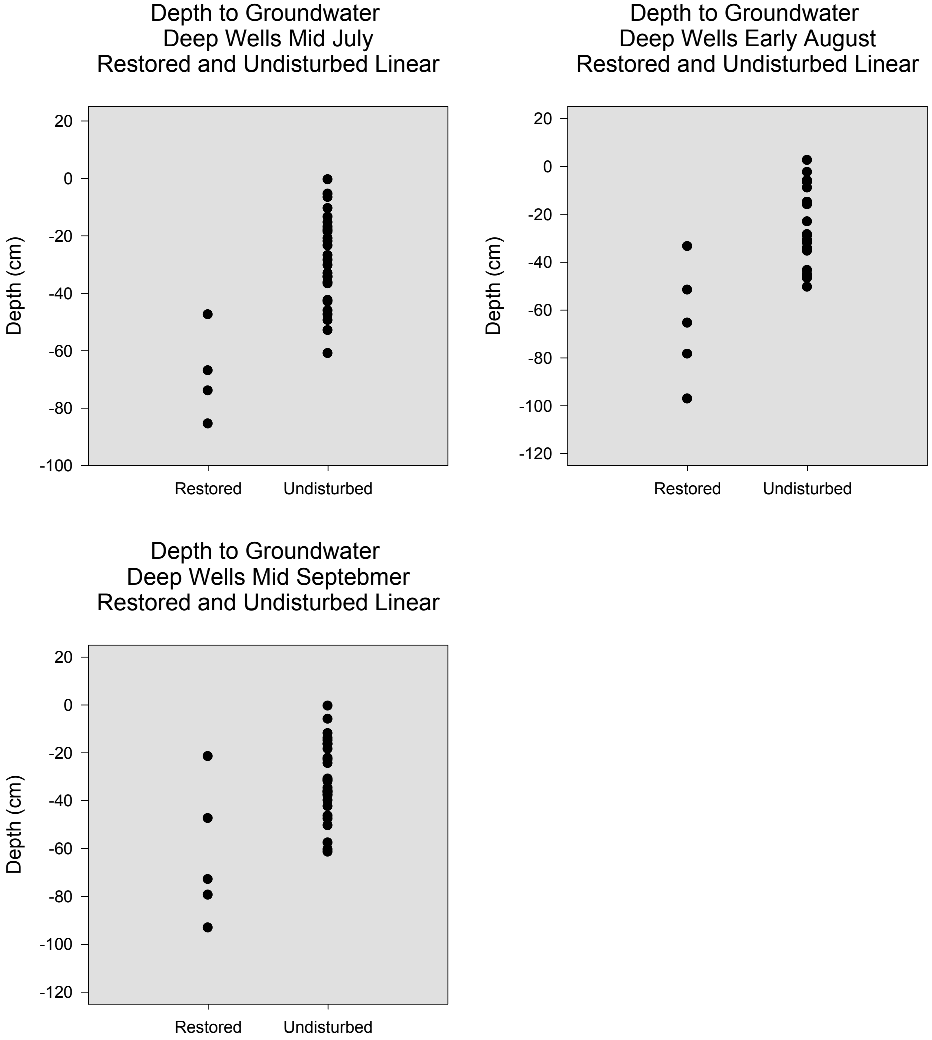

Figure 28: Depth to deep well water table in July, August and September for restored and undisturbed linear locations.

The examination of water table activity in restored linear locations also includes the persistence of shallow water (within 30 cm of surface) in both shallow and deep wells. Figure 29 illustrates that five of the seven shallow wells at linear restored locations had water within 30 cm of surface for some part of the growing season, one of which maintained saturated conditions for the length of the season. With the exception of the single well with >125 days of measurable water, the general distribution of the remaining 4 wells followed that of undisturbed sites.

Figure 30 illustrates that four of the seven deep wells at linear restored locations had water within 30 cm of surface for some part of the growing season. Of the shallow wells, three had water 25 to 45 days and a single well had water for less than 25 days.

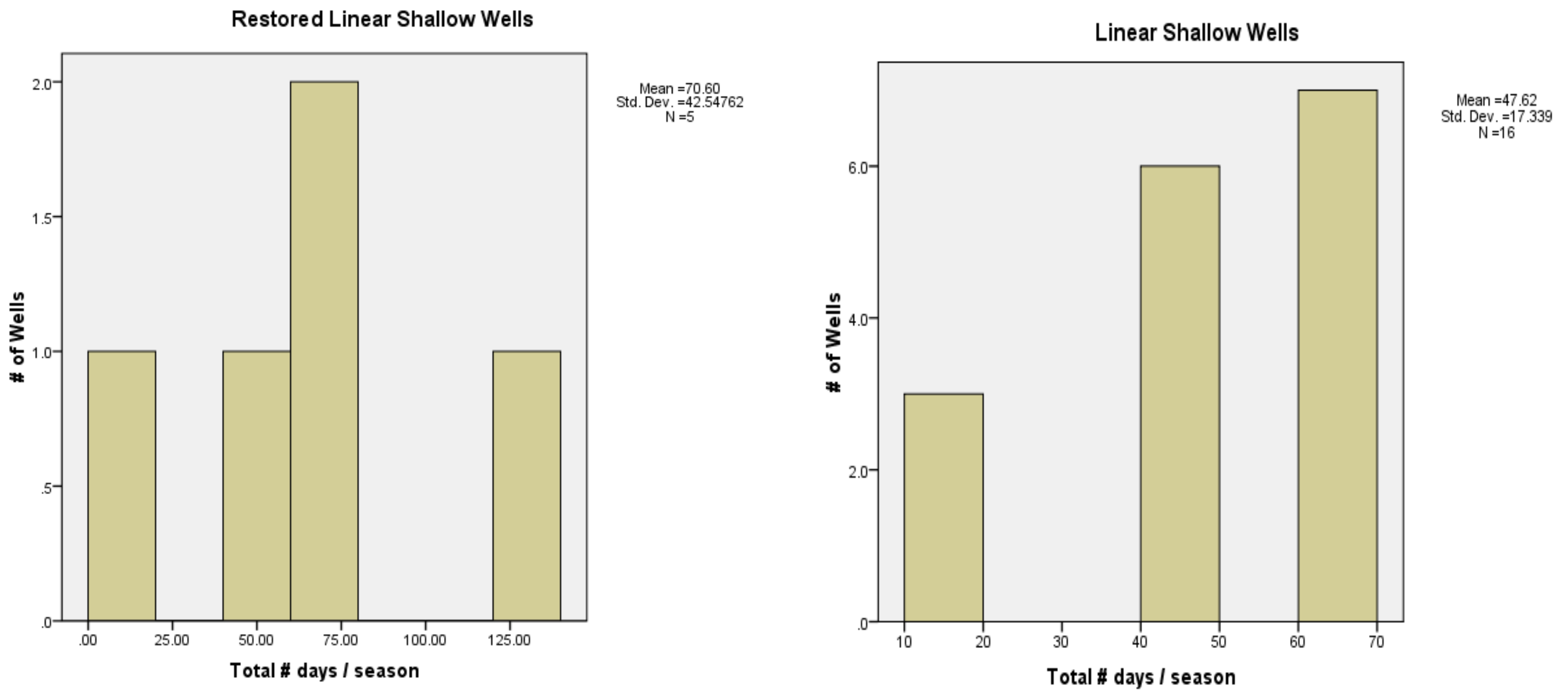

Figure 29: Shallow water table persistence for restored (left) and undisturbed (right) linear shallow wells.

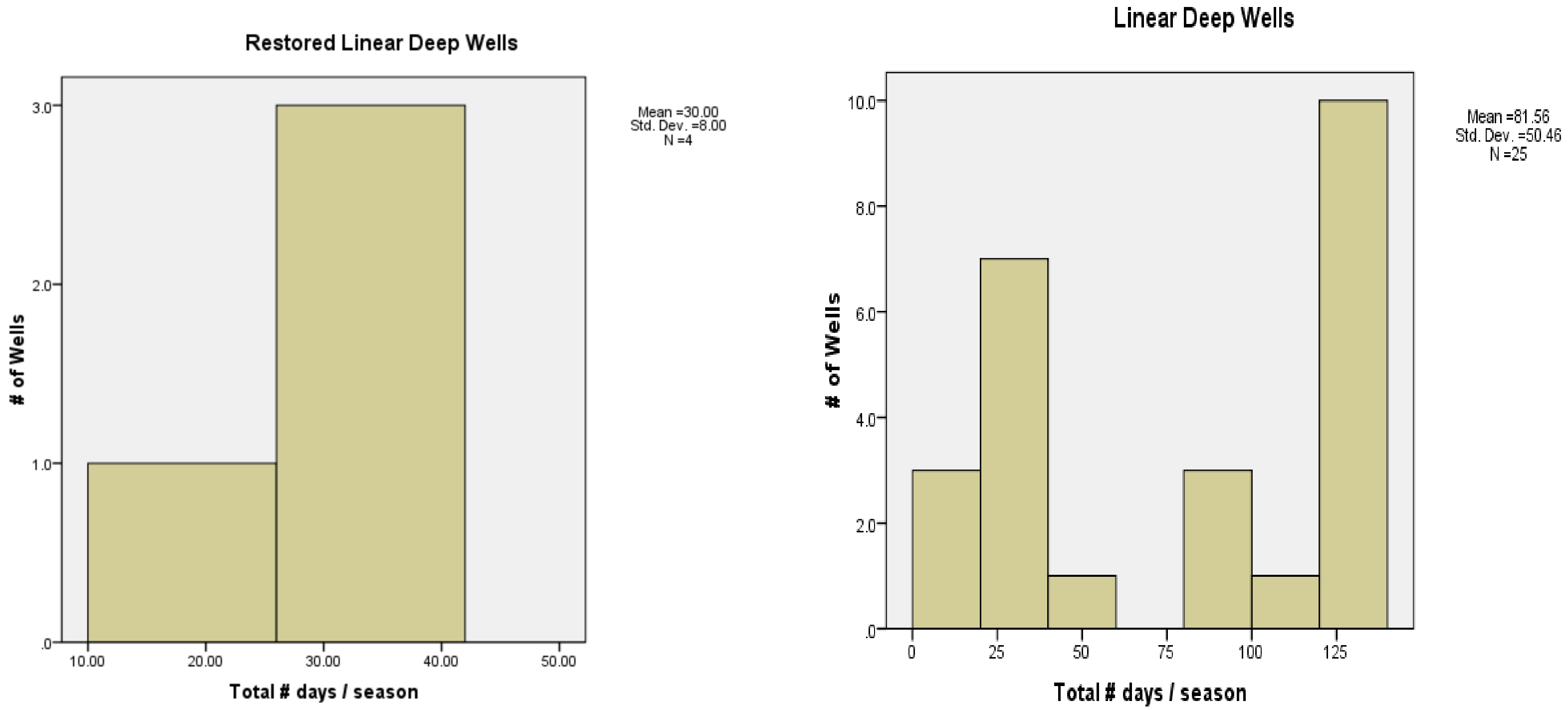

Figure 30: Shallow water table persistence for restored (left) and undisturbed (right) linear deep wells.

June deep well SC values for restored locations were distributed mostly at the lower half of the range of variability of undisturbed locations (Figure 31). This range may be attributable to the less concentrated state of solution during the higher flow period of June, which corresponds to the near surface water table activity of deep wells in restored locations during June (Figure 27).

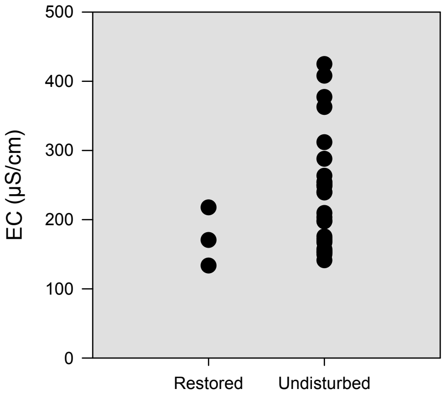

Figure 31: June deep well SC for restored and undisturbed linear locations.

Depressional

The single "restored" depressional wetland site in this study is a result of a mitigation effort to create new wetland acreage. This depressional site exhibits the same gradual slope and wide, basin-like characteristics of undisturbed depressional wetlands in this study and has a similar elevation and aspect of the majority of the sites in the study. The depressional site also differs from linear sites in overstory cover percent, a consequence of limited mature tree growth in the proximity of the site.

Vegetation: Species frequency and mean cover for depressional restored locations are compared to species frequency and mean cover for depressional undisturbed locations at all the other depressional sites in Table 24. The species in this table are the 12 species recorded for restored locations and the 20 most frequently occurring species for undisturbed locations. There are 11 common species between the two wetland conditions; *Equisetum arvense, Calamagrostis canadensis, Mitella pentandra, Carex utriculata, Veronica americana, Cirsium arvense, Epilobium anagallidifolium, Galium trifidium brandegei, Phleum pretense, Taraxacum officinale,* and *Trisetum wolfii.* In both restored and undisturbed locations, there is also one common species in the dominant communities (all species as a group with frequency >50.0 and cover > 2.0), *Calamagrostis canadensis*.

The data presented in Table 24 indicate that although some similarities exist, community composition is quite different between restored and undisturbed locations. This may be attributable to the method of construction employed at the restored depressional site, where wetland sod from an off site location was used to vegetate the area.

Table 24: Frequently occurring species of depressional restored and undisturbed locations. Noxious species are indicated in bold. Species indicated by (*) are present in both conditions but are not frequently occurring (top 20 present species) in undisturbed locations.

Species	**Depressional Undisturbed**		**Depressional Restored**	
	Frequency of Presence (%)	Mean Cover per Location (%)	Frequency of Presence (%)	Mean Cover per Location (%)
EQAR	92.500	15.538	33.330	0.083
CACA	75.000	12.488	66.670	13.833
SETR	72.500	4.000		
GERI	70.000	3.788		
ASFO	65.000	5.256		
MIPE	62.500	3.106	66.670	0.667
FRVI	55.000	2.131		
EPCI	47.500	1.506		
GLGR	42.500	2.169		
GATR	40.000	1.155		
CADI	37.500	1.013		
CAMI	37.500	2.588		
CAUT	35.000	5.481	100.000	40.583
ARMO	27.500	0.638		
ELGL	27.500	0.369		
RILA	25.000	0.563		
STCA	22.500	0.313		
VEAM	22.500	0.819	66.670	0.167
PAFI	20.000	0.329		
PYAS	20.000	0.294		
CIAR*	2.5000	0.050	66.670	1.417
EPAN*	12.500	0.518	66.670	18.583
GABR*	15.000	0.487	66.670	2.083
LIDA*			33.330	3.250
PHPR*	5.000	0.025	33.330	0.083
TAOF*	17.500	0.100	33.330	0.083
TRWO*	10.000	1.237	33.330	0.500

Similar to linear locations, critical emphasis is placed on the frequency and cover of noxious species in restored depressional locations. Two species of noxious weeds were recorded in restored locations, Canada thistle (*Cirsium arvense*) and Dalmatian toadflax (*Linaria dalmatica*). *C. arvense* was more frequent than *L. dalmatica*, while *L. dalmatica* was recorded in higher cover values than *C. arvense*. Combined cover values for both noxious species are illustrated in Figure 32, showing a comparison of mean cover per location for restored and undisturbed locations. Depressional restored locations support 4.67 % cover of noxious species as compared to 0.05% cover of noxious species at undisturbed locations.

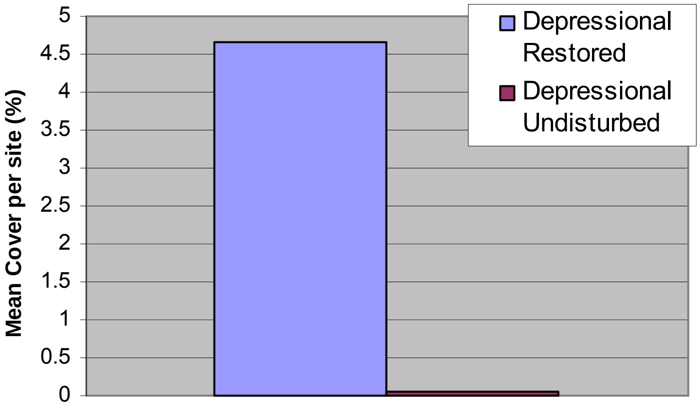

Figure 32: Mean cover of noxious weed species per location for undisturbed and restored depressional wetlands.

Several vegetation parameters indicate differences in the range of variability between wetland conditions. These parameters include moss cover, SDI, species richness, wood biomass, and herb biomass.

Moss cover, a combination of cover of all bryophytes, was zero percent at the restored depressional locations. This may be attributable to a lack of moss cover at the wetland sod source, or to an extreme level of disturbance at the site which eliminated the bryophyte community.

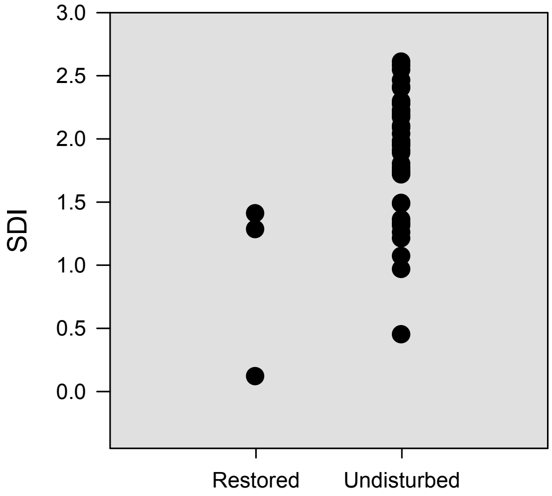

Figure 33: Shannon diversity index of restored and undisturbed depressional locations.

Shannon Diversity Index values for restored locations are distributed within and below the lower half of the normal range of variability of undisturbed locations (Figure 33). All SDI values for restored locations are below 1.5 with one data point at 0.2, below the minimum SDI values for undisturbed locations. This indicates that individuals composing the plant communities in restored locations are both less diverse and less equally distributed than many of the undisturbed locations. Similarly, Figure 34 illustrates that species richness for restored locations is distributed within and below the lower half of the range of variability for species richness of undisturbed locations. Dominance by *Carex utriculata, Epilobium anagallidifolium,* and *Calamagrostis canadensis* (Table 24) at the restored locations provide the most probable explanation for the skewed distribution of SDI and species richness

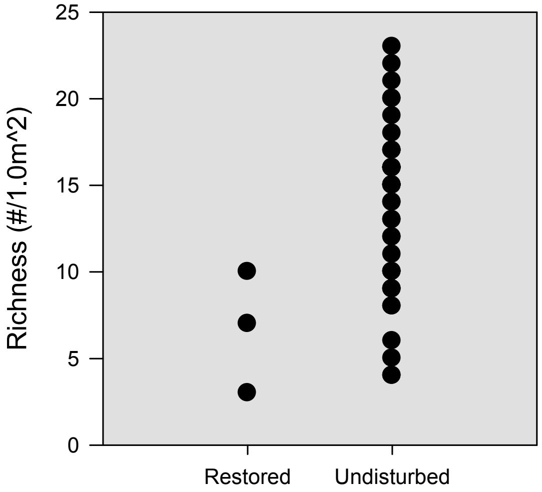

Figure 34: Plant species richness of restored and undisturbed depressional locations.

Herb biomass values also have a skewed distribution for restored locations, with all values occurring in the upper half of the range of variability of undisturbed locations Figure 35. As noted in comparisons between undisturbed linear and depressional locations, biomass can be influenced by highly productive communities of plants or highly productive species of plants. The species data for restored depressional locations indicate that the influencing factor for biomass production may be more linked to species characteristics than community characteristics in that a few large species (e.g., *Calamagrostis canadensis*) or species with extensive cover (e.g., *Carex utriculata*) may dominate the biomass productivity of a site.

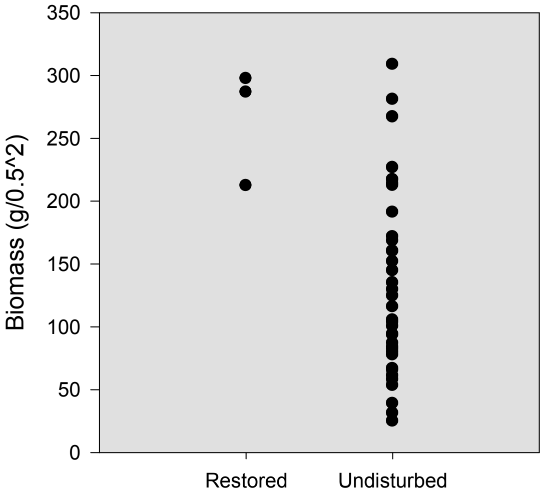

Figure 35: Herb biomass of restored and undisturbed depressional locations.

It is not possible to compare wood biomass values for restored depressional locations to undisturbed locations. Although the occurrence of wood biomass in undisturbed locations is limited, restored locations are distinct because of a total absence of woody species. As noted with linear restored locations, this implies that disturbance prior to or during restoration may have caused woody plants to be removed or destroyed resulting in a community composed primarily of herbaceous plants.

Soil: Several soil parameters show similar ranges of variability between restored and undisturbed locations. Values for July soil pH at 10 and 20 cm depths were distributed in a relatively tight cluster centered on 5.75, which is similar to the mean of undisturbed locations during the same period (5.88 and 5.73). Soil TOC at 10 and 20 cm also exhibited this clustered distribution similar to the mean of undisturbed locations (Table 5). September pH at 10 and 20 cm was distributed in a loose cluster with points throughout the range of variability of undisturbed locations. July and August soil moisture at 10 and 20 cm also exhibited this wide-spaced distribution. Texture data are lacking, due to limitation in soil sample size.

Soil redox throughout the season and August pH both exhibit notable ranges of variability in restored locations. August soil pH at 10 and 20 cm was distributed at and below the normal range of variability of undisturbed locations (Figure 36). All values are between 4.34 and 5.24, indicating strong to moderate soil acidity (Brady 1990).

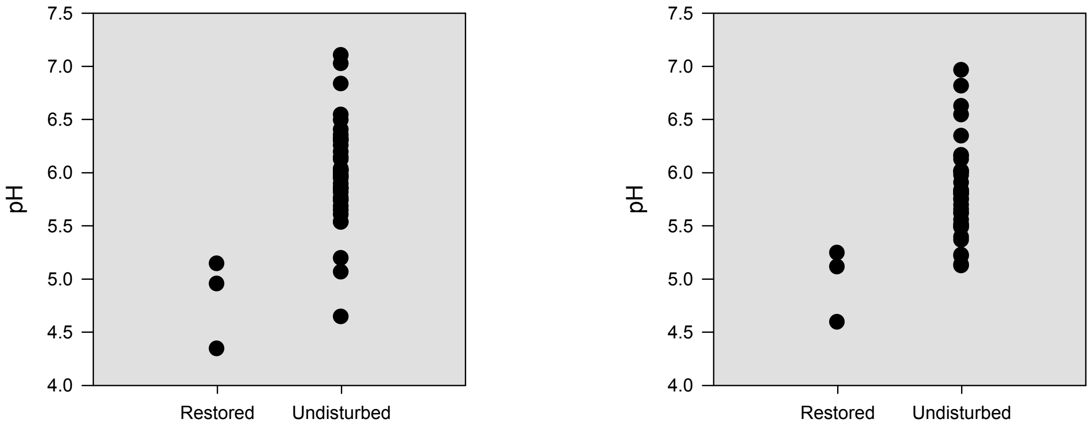

Figure 36: August soil pH at 10 cm (left) and 20 cm (right) depth for restored and undisturbed locations

Soil redox values for restored locations throughout the sampling period consistently displayed data points in the upper half of the normal range of variability of undisturbed locations (Figure 37). These data show that redox for restored locations exhibits a more oxidized state than many of the undisturbed locations. This also indicates that soils at restored locations are in the moderately reduced (facultative) redox category.

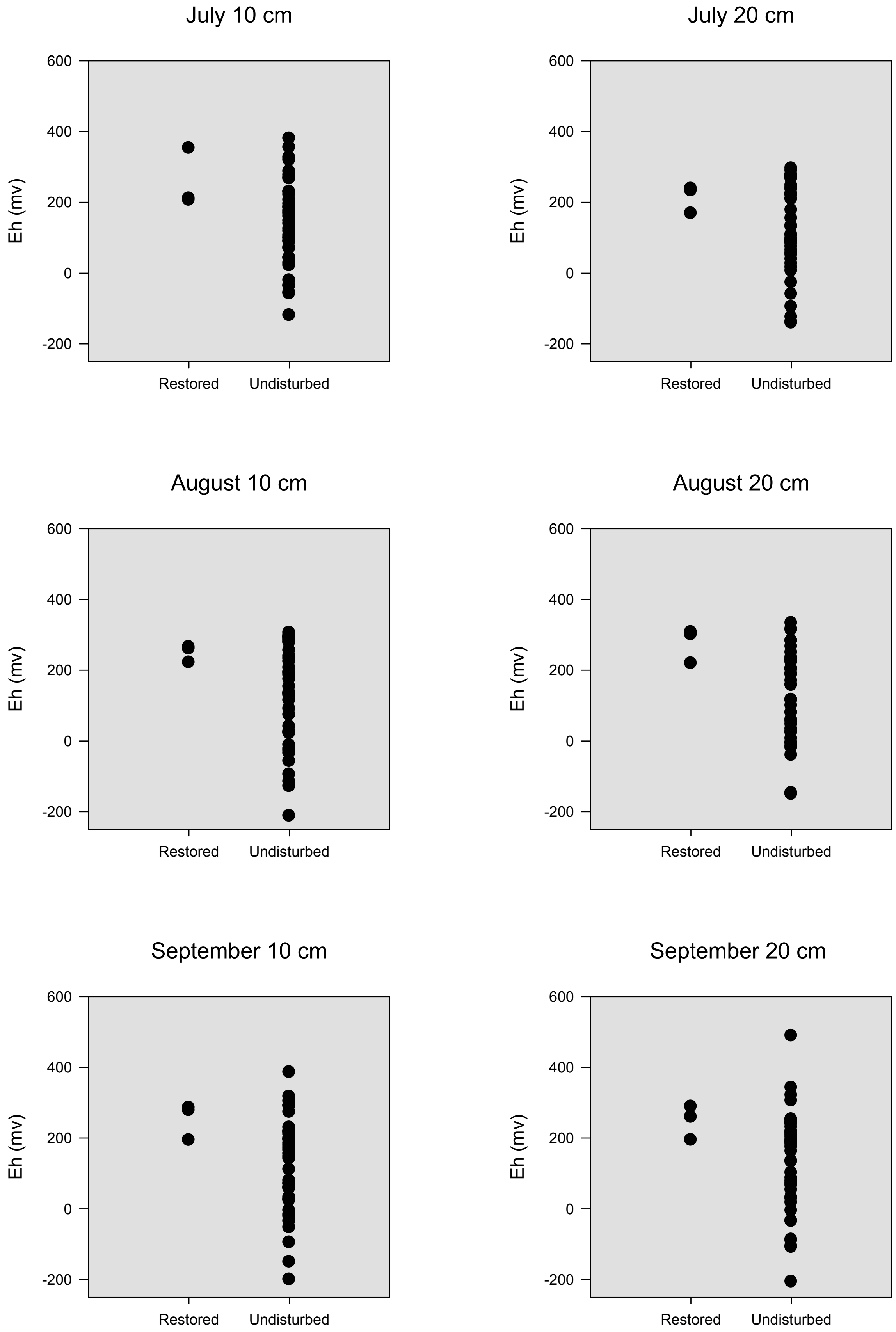

Figure 37: Redox throughout the sampling season for restored and undisturbed locations

Water: The shallow water table at restored locations never close enough to surface for measurement, consequently, this section does not include any comparison data (temperature, SC, depth) for water in shallow wells. Several water parameters from deep wells do show similarities in distribution across the range of variability for restored and undisturbed locations. Deep well water table temperatures for restored sites were distributed in a cluster at the approximate mean of undisturbed locations. Deep well SC data for restored locations were distributed widely throughout the range of variability of undisturbed sites, without any groupings toward lower or upper ranges of distribution.

A single deep well did not have recordable water level during July and September. The remaining 2 wells had water table depth data within and below the ranges of variability for undisturbed locations. Restored deep well water table data in July and September are distributed within and below the lower half of the range of variability for undisturbed sites (Figure 38). All recorded values are greater than 47 cm below surface, with the greatest depth being 116 cm below surface. As noted in previous water table discussions, it is suspected that water table activity in deep wells is influenced by the heat and lack of precipitation in July and precipitation that falls as snow and remains at the surface during September. The absence of a measurable shallow water table also provides information that may help explain the lack of near surface water table activity.

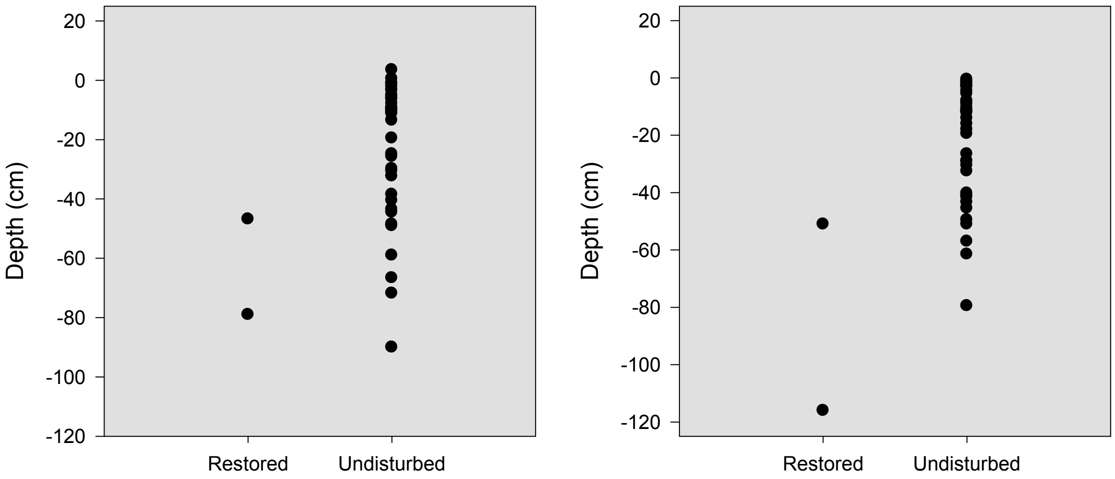

Figure 38: Depth to deep well water table July (left) and September (left) for restored and undisturbed depressional locations.

The persistence of shallow water table activity (within 30 cm of surface) was also examined for deep wells in restored depressional locations. One of the 3 deep wells recorded saturated conditions for 65 days, while the other 2 did not record any days with water table activity within 30 cm of the surface.

Discussion

While a number of parameters of restored locations exhibit a similar range of variability to undisturbed locations, the parameters which are different provide an interesting illustration of the response of small subalpine wetlands to restoration. Since many of the parameters included in this research have not been studied in the context of wetland restoration, other studies examining response to disturbance or drought are also referenced for comparison.

One important response is the presence of larger populations of noxious weeds in both linear and depressional restored locations. Noxious weeds are a global land management concern, and many studies have examined the link between disturbance activities and noxious weed populations. Hogenbirk and Wein (1991) studying northern boreal wetlands link the spread of *Cirsium arvense* (a noxious weed) with decreased water tables. Similarly, Laubhan and Schaffer (2006) conclude that incidence of *C. arvense* seed germination may be reduced by maintaining saturated soil conditions in montane wetlands. A similar species, *Linaria vulgaris,* was noted for its ability to invade higher elevation habitats of the Northern Rocky Mountains that had human and natural disturbances (Pauchard et al. 2003).

Biomass value distribution was significant in both linear and depressional restored locations. Linear locations had low woody biomass, while depressional locations had high herb biomass and no woody biomass. The literature indicates that biomass response to wetland restoration can be highly variable and can include both increases (McKenna 2003) and decreases (Fennessy et al. 2008) in primary plant production. Shrub colonization is thought to be reduced in disturbance areas in fen wetlands following construction activities (Kowalski and Wilcox 2003). We suspect that the major influence to biomass values in restored sites can be attributed to disturbance and the characteristics of certain species in restored locations.

WIS value distribution was closely aligned with undisturbed locations for linear restored locations but not depressional locations. This characteristic is critical because it is has been associated with disturbance and restoration in riparian and wetland sites. Richter and Stromberg (2005) recorded higher (drier) WIS in restored river terrace habitat compared to undisturbed. WIS has also been used to quantify the vegetation response to alteration of groundwater levels in the arid west (Stromberg et al. 1996, Patten et al. 2008). Additionally, since dominance by wetland vegetation is a metric by which wetland restoration is evaluated for success, WIS can provide insight on whether success is achieved at the most basic level.

Moss species are notably absent only at the restored depressional site. Other research indicates moss species are shown to occupy a narrow range of conditions and respond to disturbance of wetland structure. Moss communities are associated with relatively constant shallow water table and are highly correlated with soil moisture content, two characteristics that are most directly affected by ditching and draining of wetlands (Sorrell et al. 2007, Malson et al. 2008). Malson et al. (2008) noted the immediate decline of moss communities following disturbance, and limited successional reestablishment following restoration. Maintenance of soil moisture has been shown to enhance moss community establishment in restored peatlands (Cobbaert et al. 2004).

SDI and species richness values for restored depressional locations exhibited a range of variability distribution within and slightly lower than that for undisturbed locations. SDI for restored locations indicate a vegetation population less equally distributed than undisturbed locations, while richness indicate a lower number of species. These are common floristic indices used to evaluate response to disturbance and restoration. SDI of restored wetlands in Ohio were similarly low, however heavily managed created wetlands in the same study were significantly higher (Thompson et al. 2007a). Cooper and MacDonald (2000) noted that disturbed wetlands supported less than a quarter of the number of species found in undisturbed wetlands, and that revegetation efforts should be undertaken to reestablish native communities. Hajkova and Hajek (2003) alternately noted an increase in species richness following mowing operations; however the community composition was more comparable to mesic communities.

Redox values for restored locations were distributed within the range of variability for both depressional and linear locations, however, the distributions were consistently shifted toward less reduced (more oxidized) states. Redox in restored wetlands is often found to be more oxidized, but responds to the reestablishment of hydrology and saturated conditions (Sorrell et al. 2007, Hunter et al. 2008). Redox is also a useful metric for predicting the potential for establishment of specific species to restoration (Anastasiou and Brooks 2003).

Distribution of soil pH values for restored locations fell primarily within the range for undisturbed locations. However, August values of depressional locations were distributed in the lower range of undisturbed variability. A similar response was noted in created/restored headwater wetlands in North Carolina, but enormous spatial variability was noted for this wetland type (Bruland and Richardson 2005). The trend toward more oxidized soil conditions in depressional wetlands may also be influencing the low pH values recorded (Richardson and Vepraskas 2001).

Water table values for restored locations fell within and below the range of variability for both depressional and linear locations, with deep wells exhibiting low ranging distribution during mid and late summer. Shallow wells in linear locations had surface saturation only during the earliest part of summer, while shallow well data for depressional wetlands was completely lacking.

Examination of persistence of saturated conditions indicates that a comparable length of saturation was recorded for restored linear shallow wells, but that fewer deep wells had shallow water table persistence and for a smaller number of days. Both shallow and deep well persistence data in depressional locations indicate far less surface saturation than that of undisturbed locations.

More than any other characteristic, the dissimilarity of water table activity in restored locations highlights a critical point for the trajectory of these sites. As was discussed in the examination of environmental drivers, water table activity, in the form of depth and persistence, was significantly correlated with wetland function more than any other environmental parameter.

A comparable study on a mountain floodplain and wetland shows a similar response of the water table to effects of drought, where decreased precipitation events have drastically reduced the persistence of surface saturation and shallow water table discharge (Moorhead 2003). Disturbance caused decrease in water table for Great Basin wetlands is predicted to result in significant changes to the wetland plant community, shifting from a high cover monotypic stand to a community dominated by transition species (Patten et al. 2008).

SC values for restored locations were distributed within the range of variability for undisturbed locations only at linear locations, with deep well values occurring at the low end of the undisturbed range of variability. Although research on low order stream systems shows a strong positive relationship between SC and disturbance (Dow and

Zampella 2000), we suspect that SC distribution in our research is attributable to higher flow quantity and lower solute concentration.

SYNTHESIS

This study has examined several components of wetland ecology specific to wetlands found in the subalpine of the northern Rocky Mountains. Our objectives were three, (1) characterize the subalpine wetlands, (2) determine environmental drivers that influence response variables of vegetation and redox, and (3) compare undisturbed wetland characteristics to those of restored wetlands. The use of characterization not only has provided baseline information on conditions of wetlands of this region, but has allowed us to compare differences between the two wetland types, linear and depressional. Using environmental drivers we have been able to identify those conditions that influence the function of the wetlands, and examine differences and similarities in environmental drivers between the two wetland types. Through study of restored sites we have been able to examine those conditions at the two wetland types that have responded to perturbation and may be returning to a more natural state.

The results of this study imply the following conclusions, which are discussed in greater detail in the text:

- Similarities exist in conditions of both linear and depressional wetland types, likely due to the connectedness of the sites.
- Shallow water table activity defines wetland type more than any other characteristic.
- Significant differences in linear and depressional wetland types are noted for parameters in vegetation, soil and water categories. Functional

differences include metrics of biodiversity and primary productivity (for example, species richness and herb biomass).

- The speculated clay lens appears to be a more defining characteristic of depressional wetlands than linear wetlands.
- The presence of a perched water table is not conclusively proven by analysis of the water table data. The data do provide valuable information on persistence of saturation and the differing hydrologic regimes of the wetland types.
- Ecological and biogeochemical functions of both wetlands are significantly related to both soil and water parameters, with the most important factors being water table depth and soil moisture.
- A greater number of significant relationships with water parameters than soil parameters are noted for both wetland types.
- Depressional wetlands have a greater number of significant relationships with water parameters, including shallow water table activity, than do linear wetlands.
- Restored wetlands exhibit many conditions similar to those of undisturbed wetlands, but some vegetation parameters are unique to restored wetlands.
- Based on environmental driver data of undisturbed wetlands, the hydrology of restored wetlands provides information on the potential trajectory of these sites for recovery and ecological, hydrological and biogeochemical function.

Data analyzed for characterization and comparison are useful in wetland identification and classification using wetland parameters. The hydrologic regime and soil characteristics, specifically related to seasonal or permanent high water tables, classify the depressional wetlands of this study as fens or marsh meadows (Windell et al. 1986); while linear wetlands, defined by their proximity to running water and dominant plant community, are classified as herbaceous riparian wetlands (Windell et al. 1986).

Several parameters indicate that linear and depressional wetlands exhibit significantly different conditions and vegetation function, supporting the concept that these small subalpine wetland types are distinct at some levels. The different functions also provide insight on the ecological consequences of losses to these wetlands. The analysis indicates that linear wetlands function differently in biodiversity, while depressional wetlands function differently in primary production.

We think that a perched water table may be an important influence on permanent high water tables in these subalpine wetlands, and one that may be a possible cause of differences between the two wetland types. Other studies have shown that a perched water table is a result of subsurface clay (Wilson 1969, Komor 1994); however, we can not conclusively prove through analysis of shallow and deep well data that the presence of a season-long perched water table mainly in depressional wetlands was caused by a subsurface impermeable clay layer. However, our comparison of water table data do indicate some periods of significant differences between the two wetland types in depths of shallow and deep wells, but more importantly, the comparison provides an indication of the differences in temporal persistence of shallow water table activity in depressional wetlands.

The examination of environmental drivers provides additional and robust evidence that the depth to water table and the persistence of shallow water are critical drivers in defining wetland type, and have been show to be significantly correlated with a greater number of vegetation and redox response variables than any other environmental driver. However, different water table metrics are significantly related to different vegetation response variables between the wetland types. Similarly, redox has different significant correlations with environmental drivers that are unique to wetland type.

Data from restored wetlands in this study have been examined from two perspectives; first as evaluation of efficacy of restoration methods, and second as an indication of the trajectory of recovery. We found that the methods employed for restoration prove to be sufficient in establishing the primary wetland characteristics used in wetland definition, and therefore meet the criteria established by regulatory agencies. While most wetland vegetation parameters at restoration sites are comparable to undisturbed sites, an issue of concern for both wetland types undergoing restoration is the greater population of noxious weeds noted in restored sites as compared to undisturbed.

Examination of other parameters at restored sites relative to environmental drivers allows us to project possible trajectories of the restored wetland. This study indicates that water table activity is of critical importance in maintaining wetland function. While early restoration practices focused on returning flows to a disturbed wetland, the focus is now shifting toward reestablishment of the natural hydrologic regime (National Research

Council 1992, Poff et al. 1997, Patterson and Cooper 2007, Stromberg et al. 2007). In our sites, it appears reestablishment of the hydrologic regime may not be conclusively successful as the primary restoration tool, and wetland functions such as redox and vegetation are likely to have limited, albeit long term, response. Consequently, even with restoration of appropriate hydrology, future trajectories of restored wetland development may be ones of differing species composition, increases in non-native plant species, and inadequate wetland (hydric) soil development.

MANAGEMENT IMPLICATIONS

The practical implications of this study lie in the fields of land use management and restoration ecology. The products of this research are in line with recent state and federal missions addressing wetland conservation and restoration, and also have application to the future of ecosystem management.

The state of Montana recently released the Montana State Plan for Wetland Conservation and Restoration (USEPA 2008), which seeks to encourage progress in the fields of education, conservation, and restoration. Montana recognizes that the wetlands of this state are a priceless resource, and that achieving the strategic directions put forth in this document require additional research on wetland habitats and an active effort by many individuals in meeting state goals. The product of this research on small subalpine wetlands can contribute to the strategic directions of this state plan, providing information on infrequently researched wetlands that are frequently affected by development.

Additionally, the 2008 Compensatory Mitigation Final Rule released by the Army Corps of Engineers concludes that regulations are needed to “improve the quality and success of compensatory mitigation projects”, with the intent of addressing the ecological performance standards of permitted activities. These newly adopted regulations include a provision requiring that “ecological performance standards be based on the best available science that can be measured or assessed in a practicable manner”.

Finally, the growing influences of climate change may affect the structure and function of undisturbed wetlands as well as the success of wetland restoration and mitigation projects. Given the projected challenges of climate change, this study hopes to provide a historic trajectory for better informed management and restoration decisions. The baseline information provided in this study can be used to detect structural and functional changes to undisturbed subalpine wetlands over time, and also to project structural and functional changes to restored subalpine wetlands.

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APPENDICES

APPENDIX A

SPECIES LIST

Symbol	Species	Common Name	Indicator Status	Nativity
ABBI	*Abies lasiocarpa*	subalpine fir	FACU	native
ACMI	*Achilea millefolium*	yarrow	FACU	native
ACRU	*Actaea rubra*	red baneberry	UPL	native
AGST	*Agrostis stolonifera*	creeping bentgrass	FACW*	native
ALGE	*Allium geyeri*	Geyer's onion	FACU	native
ALRU	*Alnus rubra*	red alder	FAC	native
ALVI	Alnus viridis	alder	FACW	native
ANAR	Angelica arguta	Lyall's angelica	FACW	native
ARMO	*Arnica mollis*	hairy arnica	FAC	native
ARUV	*Arctostaphylos uva-ursi*	knickinick	FACU-	native
ASBO	Astragalus bourgovii	Bourgov's milkvetch	NI	native
ASFO	*Aster foliaceaus*	alpine leafybract aster	FACW-	native
BRHO	Bromus hordeaceus	soft brome	FACU	introduced
BRJA	Bromus japonicus	field brome	UPL	introduced
CAAQ	*Carex aquatilis*	water sedge	OBL	native
CAAU	*Carex aurea*	golden sedge	FACW+	native
CACA	*Calamagrostis canadensis*	blue joint reedgrass	FACW+	native
CADI	*Carex disperma*	soft leaf sedge	FACW	native
CAGE	*Carex geyeri*	Geyer's sedge	NI	native
CAMI	*Carex microptera*	smallwing sedge	FAC+	native
CAUT	*Carex utriculata*	Northwest territory sedge	OBL	native
CIAR	*Cirsium arvense*	Canada thistle	FAC-	noxious
DEEL	*Deschampsia elongata*	Slender hairgrass	FACW-	native
ELGL	*Elymus glaucus*	blue wildrye	FACU	native
ELRE	*Elymus repens*	quack grass	NI	introduced
EPAN	*Epilobium anagallidifolium*	fireweed	FACU-	native
EPCI	*Epilobium ciliatum*	fringed willowherb	FACW-	native
EQAR	*Equisetum arvense*	horsetail	FACW	native
EUCO	*Eurybia conspicua*	showy aster	NI	native
FRVI	*Fragaria virginiana*	strawberry	FACU	native
GABO	*Galium boreale*	Northern bedstraw	FACU	native
GABR	*Galium trifidium brandegei*	threepetal bedstraw	FACW+	native
GATR	*Galium triflorum*	sweet scented bedstraw	FACU	native
GEAL	Geum aleppicum	yellow avens	FACW-	native
GERI	*Geranium richardsonii*	white geranium	FAC-	native
GLGR	*Glyceria grandis*	manna grass	OBL	native
HEMA	*Heracleum maximum*	common cowparsnip	FAC+	native
HIAL	Hieracium albiflorum	hawkweed	NI	native
JUEN	*Juncus ensifolius*	mountain rush	FACW	native
JUTR	*Juncus tracyi*	Tracy's rush	FACW	native

Symbol	**Species**	**Common Name**	**Indicator Status**	**Nativity**
LIDA	*Linaria dalmatica*	Dalmatian toadflax	NI	noxious
LUPA	Luzula parviflora	smallflowered woodrush	FAC-	native
MAAQ	Mahonia aquifolium	oregon grape	NI	native
MAST	*Maianthemum stellatum*	false solomon's seal	FACW	native
MSCI	*Mertensia ciliata*	Tall fringed bluebells	FACW+	native
MIGU	*Mimulus guttatus*	Monkey flower	OBL	native
MIPE	*Mitella pentandra*	five stamened mitrewort	FAC*	native
MOSS	*All bryophytes*			
ORSE	*Orthilia secunda*	sidebells wintergreen	FAC	native
OSBE	*Osmorhiza berteroi*	sweetcicely	FACU-	native
PAFI	*Parnassia fimbriata*	grass of Parnassus	OBL	native
PEGR	Pedicularis groenlandica	elephant's head lousewort	OBL	native
PHAL	*Phleum alpinum*	mountain timothy	FACW	native
PHPR	*Phleum pratense*	field timothy	FACU	introduced
PICO	*Pinus contorta*	Lodgepole pine	FAC	native
PIEN	*Picea engelmanii*	engelman's spruce	FAC	native
PLDI	*Plantanthera dilitata*	tall white rein orchid	FACW	native
POPA	*Poa palustris*	fowl bluegrass	FACW	native
PYAS	*Pyrola americana*	American wintergreen	FAC	native
RAAC	Ranunculus acris	buttercup	FAC+	native
RIHU	*Ribes hudsonianum*	Northern black currant	FACW	native
RILA	*Ribes lacustre*	black gooseberry	FAC+	native
ROWO	*Rosa woodsii*	wood's rose	FACU	native
SAME	*Salix melanopsis*	dusky willow	OBL	native
SAOC	*Saxifraga odontoloma*	brook saxifrage	FACW	native
SETR	*Senecio triangularis*	arrowleaf groundsel	FACW+	native
SPBE	Spiraea betulifolia	spirea	FACU*	native
STAM	*Streptopus amplexifolius*	claspleaf twisted stalk	FAC-	native
STCA	*Stellaria calycantha*	northern starwort	FACW	native
TAOF	*Taraxacum officinale*	dandelion	FACU	NI
THOC	*Thalictrum occidentale*	meadow ruh	FACU*	native
TRAU	*Trifolium aureum*	clover	NI	introduced
TRBE	*Trifolium beckwithii*	Beckwith's clover	FAC	native
TRWO	*Trisetum wolfii*	Wolf's trisetum	FACU	native
VAME	*Vaccinium membranaceum*	thin leaf huckleberry	FACU	native
VASC	*Vaccinium scoparium*	grouseberry	FACU-	native
VEAM	*Veronica americana*	american speedwell	OBL	native
VIOR	*Viola orbiculata*	darkwoods violet	NI	native

APPENDIX B

CORRELATIONS

Undisturbed Linear Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Vegetation Cover	P																
LogN of Moss Cover	P	-.469(*)															
LogN of Bare Ground Cover	P	-0.093	0.178														
Wetland Indicator Score	P	-0.01	0.029	0.242													
Richness	P	0.08	0.042	0.404	.518(**)												
Shannon Diversity Index	P	0.247	0.061	.467(*)	.631(**)	.836(**)											
Non Native Vegetation Cover	S	0.193	-0.374	0.19	0.346	-0.159	-0.09										
Native Vegetation Cover	P	.983(**)	-.458(*)	-0.082	-0.067	0.105	0.26	0.087									
LogN of Herb Biomass	P	0.144	-0.139	-0.265	-0.309	-0.239	-0.306	0.042	0.108								
LogN of Wood Biomass	P	-0.166	0.334	0.378	0.097	0.115	-0.166	-0.543	-0.156	0.097							
July Redox 10 cm	P	0.032	-0.253	0.062	0.126	0.173	0.28	0.099	0.054	-.476(*)	-0.466						
July Redox 20 cm	P	0.24	-.469(*)	-0.02	0.202	0.17	0.278	0.298	0.253	-0.211	-.552(*)	.745(**)					
August Redox 10 cm	P	0.276	-0.38	-0.171	0.351	0.269	.426(*)	0.193	0.279	0.191	-0.427	.377(*)	.562(**)				
August Redox 20 cm	P	.522(**)	-0.405	-0.17	0.178	0.179	0.32	0.135	.512(**)	0.273	-0.467	0.316	.603(**)	.806(**)			
September Redox 10 cm	P	0.132	-0.157	-0.02	0.026	-0.059	0.138	-0.117	0.137	0.02	-0.125	0.246	0.325	0.135	0.194		
September Redox 20 cm	S	0.202	-0.194	-0.154	-0.097	-0.046	-0.045	0.308	0.206	-0.15	-0.293	.491(**)	.633(**)	0.187	0.371	.692(**)	
July pH 10 cm	P	-0.345	0.004	0.056	-0.193	0.054	-0.235	0.04	-0.362	0.325	-0.179	-0.307	-0.22	-0.238	-0.144	-0.144	-0.082
July pH 20 cm	P	-0.264	-0.032	0.201	-0.105	0.039	-0.149	-0.035	-0.272	-0.013	0.08	-0.358	-0.34	-.455(*)	-.497(**)	-0.215	-0.365
August pH 10 cm	P	-.404(*)	-0.025	0.03	-0.02	-0.133	-0.271	0.026	-.424(*)	0.021	0.036	-0.134	-0.1	-0.146	-.377(*)	-0.034	0.023
August pH 20 cm	P	-.483(*)	0.107	0.053	0.058	0.037	-0.141	-0.097	-.516(**)	0.001	-0.077	-0.043	-0.121	-0.049	-0.306	-0.047	-0.071
September pH 10 cm	P	-.486(*)	0.041	-0.046	-0.088	-0.003	-0.309	-0.377	-.481(*)	0.159	0.231	-0.282	-0.294	-0.142	-0.158	-0.322	-0.368

Undisturbed Linear Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
September pH 20 cm	P	-0.296	-0.224	0.2	0.023	-0.032	-0.17	-0.157	-0.304	0.03	0.042	-0.286	-0.21	-0.112	-0.225	-0.17	-.406(*)
Moisture July 10 cm	P	-.649(**)	0.251	0.209	-0.036	0.121	-0.061	-0.427	-.622(**)	-0.025	0.308	-0.102	-0.336	-0.154	-0.371	-0.143	-0.316
Moisture July 20 cm	P	0.156	-0.191	0.214	-0.067	0.155	0.104	-0.205	0.141	-0.079	0.007	0.039	-0.246	-0.129	-0.315	0.016	-0.198
Moisture August 10 cm	S	-.492(**)	0.433	-0.029	-0.057	-0.035	-0.186	-0.322	-.475(*)	0.152	0.122	-.408(*)	-.493(**)	-0.219	-.423(*)	-.412(*)	-.527(**)
Moisture August 20 cm	S	-0.225	0.142	0.06	0.227	0.168	0.061	-0.307	-0.218	-0.152	0.014	0.032	-0.196	-0.054	-0.212	-.397(*)	-.468(*)
LogN of TOC 10 cm	P	-0.343	0.38	0.08	.414(*)	0.317	.430(*)	-0.126	-0.293	-.436(*)	0.01	.477(*)	0.219	.393(*)	0.077	-0.185	-0.126
LogN of TOC 20 cm	P	-0.366	0.059	0.051	.518(**)	0.285	0.29	0.062	-0.381	-0.372	0.048	0.321	0.026	0.254	-0.039	-0.12	-0.168
Sand content 10 cm	P	0.001	-0.234	0.168	0.054	-0.329	-0.167	0.289	-0.002	-0.564	0.06	-0.329	-0.394	-0.399	-0.445	-0.422	-0.221
Silt content 10 cm	P	-0.07	0.25	-0.081	-0.031	0.236	0.115	0.026	-0.132	.606(*)	-0.019	0.076	0.17	0.152	0.181	0.389	0.092
Clay content 10 cm	P	0.084	0.181	-0.23	-0.07	0.376	0.197	-0.676	0.166	0.399	-0.125	0.572	.587(*)	.621(*)	.677(*)	0.372	0.149
Sand content 20 cm	P	0.224	-0.021	-0.192	-0.098	-.557(**)	-0.407	0.009	0.234	-0.072	0.184	-0.17	-0.072	0.006	0.012	-0.008	-0.036
Silt content 20 cm	P	-0.132	-0.324	-0.005	-0.186	-0.084	-0.303	0.083	-0.196	.560(**)	-0.085	-0.329	-0.01	-0.027	0.117	0.059	0.173
LogN of Clay Content 20 cm	P	-0.117	0.129	0.283	0.222	.615(**)	.540(*)	-0.106	-0.082	-0.252	-0.168	0.328	0.072	0.046	-0.064	-0.076	-0.163
Clay depth	P	-.561(**)	0.046	-0.186	0.17	0.107	-0.084	-0.321	-.538(**)	-0.205	-0.186	0.065	-0.038	0.077	-0.213	0.094	-0.135
Deep Well Early June	P	0.053	-0.119	-0.177	-0.37	-0.194	-0.365	-0.129	0.04	0.253	0.123	-.389(*)	-0.275	-0.264	-0.224	-0.251	-0.294
Shallow Well Early June	P	0.331	-1.000(**)	0.46	-0.18	-0.296	-0.104	-1.000(**)	0.368	0.557	-0.735	0.25	0.656	0.568	0.747	0.773	0.738
Deep Well Late June	P	0.098	-0.099	0.019	-0.383	-0.272	-0.341	-0.085	0.064	0.322	0.305	-.438(*)	-.448(*)	-0.173	-0.132	-0.074	-0.222
Shallow Well Late June	P	-0.725	1.000(**)	-0.995	-0.157	-0.898	-0.761	-1.000(**)	-0.893	0.738	0.989	-0.939	-0.746	0.376	0.308	-0.32	-0.4
Deep Well Mid July	P	-0.175	0.013	0.012	-.590(**)	-.409(*)	-.589(**)	-0.314	-0.161	0.202	0.525	-.429(*)	-.412(*)	-.551(**)	-.483(*)	-0.163	-0.123
Shallow Well Mid July	P	-0.41	0.642	-0.258	-0.205	-0.187	-0.36	-0.41	-0.371	-0.386	0.768	-0.509	-.767(*)	-.668(*)	-0.596	-.709(*)	-.733(*)
Deep Well Early August	P	-0.036	0.062	-0.103	-.529(**)	-0.225	-.450(*)	-0.157	-0.029	.476(*)	.541(*)	-.527(**)	-.402(*)	-.448(*)	-0.369	-0.269	-0.05

Undisturbed Linear Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Shallow Well Early August	S	0.131	0.214	-0.561	-0.293	-0.048	-0.29	-0.479	0.134	0.17	.695(*)	-0.247	-0.243	-0.088	0.027	-0.326	-0.214
Deep Well Mid September	P	-0.044	-0.003	-0.284	-0.317	-0.231	-.383(*)	-0.117	-0.061	0.187	0.247	-.493(**)	-.419(*)	-.468(*)	-.496(**)	-0.253	-0.212
Shallow Well Mid September	P	0.206	0.142	0.22	0.158	0.337	0.214	0.012	0.203	0.157	.887(**)	-0.379	-0.325	-0.104	-0.145	-0.356	-0.344
Temperature Deep Well June	P	-0.079	-0.03	-0.031	-.390(*)	-0.28	-0.353	0.071	-0.078	.417(*)	0.191	-0.244	-0.037	-0.018	0.133	0.188	0.349
Temperature Shallow Well June	S	-0.447	.	-0.866	0	-0.894	-0.447	.	-0.447	0.894	0.866	-0.894	-0.447	0.894	0.894	0	-0.447
LogN of SC Deep Well June	P	-0.124	0.215	-0.06	-0.111	0.151	0.065	-0.099	-0.138	0.116	-0.232	-0.215	-0.214	-0.168	-0.212	-0.03	-0.238
SC Shallow Well June	P	-0.493	1.000(**)	0.472	-0.439	0.394	-0.124	-1.000(**)	-0.308	-0.571	0.113	0.242	-0.087	-.960(*)	-.976(*)	-0.136	0.4
Temperature Deep Well July	P	0.139	-0.026	-0.253	-0.241	-0.052	-0.286	0.284	0.1	.718(**)	0.115	-.634(**)	-0.286	-0.083	0.031	-0.183	-0.229
Temperature Shallow Well July	P	0.173	0.241	-0.421	-0.347	-0.075	-0.098	-0.982	0.222	0.419	0.938	-.759(*)	-0.681	-0.201	0.312	-0.185	-0.611
SC Deep Well July	P	-0.111	0.297	-0.08	-0.351	0.102	-0.033	-0.516	-0.018	0.137	-0.232	-0.197	-0.298	-0.213	-0.252	-0.089	-.410(*)
SC Shallow Well July	P	-0.469	0.794	-0.86	0.2	0.116	-0.226	0.866	-0.489	-0.451	0.207	-0.085	-0.437	-0.196	-0.628	-0.546	-0.107
Temperature Deep Well August	P	0.286	-.477(*)	0.117	-0.27	0.012	-0.1	0.111	0.243	.566(**)	-0.111	-.472(*)	-0.113	0.01	0.212	-0.092	-0.068
Temperature Shallow Well August	P	.644(*)	-0.507	0.486	-0.27	0.18	0.053	0.123	.647(*)	0.277	-0.028	-0.258	0.04	-0.037	0.255	0.125	0.123
SC Deep Well August	P	-0.279	0.409	-0.309	-0.193	-0.09	-0.16	-0.404	-0.247	0.13	-0.032	-0.333	-.587(**)	-0.122	-0.321	-.609(**)	-.661(**)
SC Shallow Well August	P	-0.445	0.581	-0.513	0.253	-0.01	-0.035	-0.22	-0.454	-0.407	-0.177	0.081	-0.202	0.036	-0.242	-0.327	-0.361
Deep wells: # days water <-30 cm	S	0.003	-0.080	-0.109	-0.455(*)	-.413(*)	-.460(*)	-0.320	0.012	0.159	0.340	-.440(*)	-0.314	-0.299	-0.354	-0.223	-0.193

Undisturbed Linear Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Shallow wells: # days water <-30 cm	S	-0.252	0.192	-0.122	-0.213	0.029	-0.324	-0.428	-0.195	0.095	0.459	-0.230	-0.339	-0.159	-0.363	-0.262	-0.313

** significant at the 0.01 level (2-tailed), * significant at the 0.05 level (2-tailed).

Undisturbed Depressional Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Vegetation Cover	P																
LogN of Moss Cover	P	-0.129															
LogN of Bare Ground Cover	P	-0.185	.382(*)														
Wetland Indicator Score	P	-0.014	0.188	.388(*)													
Richness	P	0.066	0.02	0.197	.600(**)												
Shannon Diversity Index	P	0.167	0.189	.389(*)	.706(**)	.827(**)											
Non Native Vegetation Cover	S	0.214	-0.107	0.113	0.273	0.327	0.179										
Native Vegetation Cover	P	.998(**)	-0.125	-0.196	-0.033	0.051	0.157	0.003									
LogN of Herb Biomass	P	0.246	-0.137	0.094	-0.309	-.336(*)	-0.274	-0.371	0.249								
LogN of Wood Biomass	P	0.287	-0.331	-0.195	-0.102	-0.268	-0.397	0.5	0.255	-0.069							
July Redox 10 cm	P	-0.038	0.121	-0.191	0.112	0.12	-0.049	.629(*)	-0.052	-.394(*)	0.231						
July Redox 20 cm	S	0.024	0.078	-0.138	.321(*)	.324(*)	0.204	0.353	0.014	-.475(**)	-0.048	.665(**)					
August Redox 10 cm	S	0.062	-0.046	-.495(**)	0.089	0.022	-0.097	0.396	0.052	-.398(*)	.714(*)	.552(**)	.590(**)				
August Redox 20 cm	P	0.045	-0.077	-0.268	0.262	0.149	0.037	0.191	0.027	-.397(*)	0.389	.472(**)	.665(**)	.771(**)			
September Redox 10 cm	P	0.054	0.166	-0.144	-0.071	-0.047	-0.014	0.065	0.049	-.329(*)	0.417	.402(*)	0.265	.563(**)	.387(*)		
September Redox 20 cm	P	-0.224	0.174	0.15	.418(**)	0.311	.414(**)	0.037	-0.227	-.433(**)	-0.128	0.236	.329(*)	.422(**)	.409(**)	.456(**)	
July pH 10 cm	P	-0.056	0.045	-0.012	0.21	0.231	0.236	-0.5	-0.052	0.079	0.143	-0.202	-0.111	-0.178	0.062	-0.141	-0.078
July pH 20 cm	P	0.077	-0.036	0.03	0.024	0.089	0.079	-.760(**)	0.093	0.031	0.055	-.322(*)	-0.163	-0.27	-0.263	-.350(*)	-0.291
August pH 10 cm	P	-0.009	0.31	0.182	0.009	0.134	0.022	0.083	0.001	0.205	-0.119	-0.114	-0.242	-.435(**)	-.423(**)	-.389(*)	-.379(*)
August pH 20 cm	P	-0.02	0.043	0.124	-0.183	-0.019	0.008	0.37	-0.027	0.202	0.023	0.023	-0.282	-.387(*)	-.516(**)	-0.209	-.395(*)

Undisturbed Depressional Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
September pH 10 cm	P	-0.144	-0.193	0.104	0.033	0.148	0.076	0.429	-0.16	0.051	-0.223	0.034	-0.002	-0.196	-.334(*)	-.375(*)	-.375(*)
September pH 20 cm	P	-0.032	0.085	0.015	0.061	0.046	0.225	0.248	-0.031	0.02	0.003	-0.091	-0.097	-.320(*)	-.401(*)	-0.241	-0.124
Moisture July 10 cm	S	0.223	0.079	0.179	-0.201	-0.162	0.012	-0.501	0.245	0.295	0.024	-.491(**)	-.505(**)	-.459(**)	-.590(**)	-0.123	-.387(*)
Moisture July 20 cm	P	0.194	0.221	0.099	-.352(*)	-0.218	-0.091	-0.293	0.206	0.31	-0.082	-0.298	-.523(**)	-.384(*)	-.545(**)	0.002	-0.235
Moisture August 10 cm	S	0.185	0.077	0.212	-0.305	-0.096	0.021	-0.276	0.203	.327(*)	-0.071	-.417(**)	-.555(**)	-.554(**)	-.780(**)	-0.166	-.395(*)
Moisture August 20 cm	P	0.144	0.254	0.164	-.400(*)	-0.215	-0.133	0.094	0.156	0.307	-0.03	-0.186	-.394(*)	-.382(*)	-.569(**)	0.024	-0.273
LogN of TOC 10 cm	P	-0.009	0.199	-0.073	-0.099	-0.055	-0.074	-0.028	0.004	-0.152	0.247	0.056	-0.182	-0.04	-0.235	0.231	0.101
LogN of TOC 20 cm	P	0.041	0.263	0.172	-0.265	-0.149	-0.079	0.037	0.05	0.116	0.047	-0.111	-0.302	-0.251	-.404(**)	0.078	-0.113
Sand content 10 cm	P	0.452	-1.000(**)	-1.000(**)	-0.36	-0.347	0.586	0.866	0.506	0.709	.(a)	0.055	-0.105	-0.105	0.325	0.512	0.559
Silt content 10 cm	P	-0.353	.(a)	.(a)	0.364	0.239	0.995	0	-0.315	-0.076	.(a)	-0.71	-0.632	-0.632	-0.449	-0.323	.977(*)
Clay content 10 cm	P	0.022	1.000(**)	1.000(**)	-0.07	0.005	-0.984	-0.5	-0.028	-0.274	.(a)	0.432	0.4	0.4	0.141	-0.025	-0.884
Sand content 20 cm	P	0.012	0.158	0.022	-0.015	-0.045	0.244	0.053	0.016	-0.126	-0.408	0.121	0.212	-0.126	0.096	0.332	0.159
Silt content 20 cm	P	-0.003	0.164	0.158	0.417	0.377	.501(*)	0.152	-0.013	-0.186	0.625	0	-0.078	0.023	-0.225	0.17	-0.007
LogN of Clay Content 20 cm	P	-0.002	-0.184	-0.073	-0.259	-0.195	-0.426	0.079	-0.002	0.227	-0.059	-0.162	-0.017	0.088	0.13	-0.353	-0.13
Clay depth	P	0.06	-0.049	-0.115	0.041	0.107	0.094	-0.216	0.076	-0.131	-0.244	0.008	-0.104	-0.048	-0.082	0.189	0.104
Deep Well Early June	S	0.162	0.091	0.151	-.390(*)	-0.29	-0.144	-0.168	0.163	.515(**)	-0.607	-.438(**)	-.358(*)	-.364(*)	-0.298	-0.306	-.372(*)
Shallow Well Early June	P	-0.089	-0.297	0.538	0.063	-0.352	-0.074	0.188	-0.084	0.653	1.000(**)	-0.397	-0.049	-0.024	-0.095	-0.203	-0.149
Deep Well Late June	S	0.259	-0.03	0.08	-0.094	-0.318	0.036	-0.122	0.259	.382(*)	-0.321	-.416(*)	-0.195	-0.286	-0.106	-0.31	-0.264
Shallow Well Late June	P	0.006	-0.499	0.124	-0.259	-0.409	-0.25	0.525	0.011	0.517	1.000(**)	-0.434	-0.524	-0.238	-0.336	-0.228	-0.394
Deep Well Mid July	S	0.034	-0.182	0.318	-0.164	-0.022	0.071	-0.022	0.037	.415(*)	-.786(*)	-.689(**)	-.662(**)	-.680(**)	-.796(**)	-.624(**)	-.475(**)
Shallow Well Mid July	P	-0.03	-0.269	0.081	-0.138	-0.402	-0.351	0.009	-0.008	.582(**)	0.414	-.777(**)	-.575(**)	-.507(*)	-.454(*)	-.567(**)	-0.382

Undisturbed Depressional Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Deep Well Early August	S	0.069	-0.135	0.361	-0.195	-0.121	0.065	0.031	0.062	.498(**)	-0.357	-.684(**)	-.643(**)	-.678(**)	-.654(**)	-.557(**)	-.435(**)
Shallow Well Early August	P	-0.048	-0.108	0.275	-0.079	-0.242	-0.144	-0.234	-0.025	.477(*)	-0.428	-.689(**)	-.648(**)	-.691(**)	-.703(**)	-.556(**)	-0.214
Deep Well Mid September	S	-0.07	-0.154	.435(*)	-0.126	-0.083	0.041	-0.097	-0.075	0.336	0.143	-.692(**)	-.695(**)	-.660(**)	-.622(**)	-.593(**)	-.358(*)
Shallow Well Mid September	P	0.001	0.06	.451(*)	-0.095	-0.17	-0.158	-0.198	0.016	.392(*)	-0.516	-.414(*)	-.426(*)	-.512(**)	-0.307	-.475(*)	-0.252
Temperature Deep Well June	P	-0.132	-0.283	0.017	0.211	-0.063	-0.042	0.226	-0.148	0.121	0.689	-0.099	-0.065	0.221	0.116	-0.075	-0.038
Temperature Shallow Well June	P	0.057	0.682	-0.171	-0.299	-0.25	-0.326	0.46	0.059	-0.066	1.000(**)	0.017	0.27	0.396	0.022	0.471	0.099
LogN of SC Deep Well June	P	-0.197	0.033	0.229	0.02	-0.068	-0.191	0.23	-0.215	0.206	.802(*)	-0.154	-0.055	-0.128	-0.125	-0.187	-0.177
SC Shallow Well June	P	0.12	-0.656	0.005	-0.233	-0.298	-0.204	0.309	0.117	0.434	1.000(**)	-0.079	-0.31	-0.071	-0.161	-0.214	-0.459
Temperature Deep Well July	S	0.08	-0.347	0.104	-0.293	-0.199	-0.084	-0.171	0.083	.397(*)	-0.385	-.437(**)	-.373(*)	-0.142	-0.154	-0.118	-0.155
Temperature Shallow Well July	S	0.138	-0.35	0.11	-0.126	-0.127	-0.097	-0.34	0.136	.524(*)	0.8	-.641(**)	-0.32	-0.13	0.067	-0.316	-0.166
SC Deep Well July	P	-0.091	-0.176	0.189	-0.072	-0.236	-0.334	-0.372	-0.094	.541(**)	-0.021	-0.076	-0.053	-0.236	-0.08	-0.278	-.386(*)
SC Shallow Well July	P	-0.235	-.540(**)	-0.116	-0.006	0.004	-0.13	-0.133	-0.23	0.097	-0.686	-0.204	-0.002	-.482(*)	-0.185	-.784(**)	-0.404
Temperature Deep Well August	P	0.084	-0.061	0.112	0.12	-0.07	-0.052	-0.042	0.09	0.107	-0.284	-0.087	-0.102	0.048	0	0.119	0.085
Temperature Shallow Well August	P	0.08	-0.103	-0.03	0.319	0.16	0.17	-0.391	0.085	0.192	0.135	-0.051	-0.077	0.148	0.338	0.143	0.197
SC Deep Well August	P	-0.259	-0.207	0.191	-0.082	0.116	0.019	-0.51	-0.248	.393(*)	-0.422	-0.211	-0.267	-.543(**)	-.473(**)	-.486(**)	-0.322
SC Shallow Well August	P	-0.03	-0.23	-0.113	0.041	0.133	0.093	0.256	-0.031	0.027	-0.282	0.06	-0.157	-.447(*)	-.365(*)	-.487(**)	-.421(*)
Deep wells: # days water <-30 cm	S	0.002	-0.062	.358(*)	0.049	0.189	0.236	0.101	-0.016	0.024	-0.464	-.558(**)	-.465(**)	-.493(**)	-0.380(*)	-.375(*)	-0.140

Undisturbed Depressional Locations	Correlation Method (P=Pearson's, S=Spearman's)	Vegetation Cover	LogN of Moss Cover	LogN of Bare Ground Cover	Wetland Indicator Score	Richness	Shannon Diversity Index	Non Native Vegetation Cover	Native Vegetation Cover	LogN of Herb Biomass	LogN of Wood Biomass	July Redox 10 cm	July Redox 20 cm	August Redox 10 cm	August Redox 20 cm	September Redox 10 cm	September Redox 20 cm
Shallow wells: # days water <-30 cm	S	0.155	-0.148	.404(*)	0.025	0.053	0.137	-0.281	0.150	.343(*)	-0.383	-.591(**)	-.450(**)	-.547(**)	-.495(**)	-.503(**)	-.402(*)

** significant at the 0.01 level (2-tailed), * significant at the 0.05 level (2-tailed).

Pearson’s Correlation for DCA Plot	Axis 1	Axis 2
Axis 1	1	-0.047
Axis 2	-0.047	1
Axis 3	0.158	0.124
July_redox 10cm	-.305(**)	-0.102
July_redox_20cm	-.279(*)	0.02
Aug_redox_10cm	-0.184	-0.103
Aug_redox_20cm	-0.116	0.006
Sept_redox_10cm	-0.121	-.228(*)
Sept_redox_20cm	-0.082	0.019
pH_June_July_10cm	-0.001	0.127
pH_June_July_20cm	0.018	0.013
pH_August_10cm	-0.204	0.016
pH_August_20cm	-.281(*)	-0.056
pH_Sept_10cm	-0.009	0.025
pH_Sept_20cm	-0.125	-0.085
Moisture_July_10cm	.233(*)	-0.012
Moisture_July_20cm	0.192	-0.097
Moisture_August_10cm	0.135	-0.023
Moisture_August_20cm	0.139	-0.139
TOC_10cm	0.01	0.048
TOC_20cm	0.172	0.013
%sand_10cm	-0.212	-0.229
%silt_10cm	0.275	0.241
%clay_10cm	0.111	0.163
%sand_20cm	-0.192	-.287(*)
%silt_20cm	0.006	0.033
%clay_20cm	0.153	0.216
Clay_depth	-.247(*)	0.041
Deep_well_early_June	.282(*)	-0.049
Shallow_well_early_June	.704(**)	0.173
Deep_well_late_June	0.183	-0.156
Shallow_well_late_June	.637(*)	0.07
Deep_well_mid_July	0.104	-0.217
Shallow_mid_July	.497(**)	0.215
Deep_well_early_Aug	.296(*)	-0.208
Shallow_early_Aug	.479(**)	0.196
Deep_mid_Sept	0.11	-0.036
Shallow_mid_Septe	.434(**)	.335(*)
Temp_deep_June	.271(*)	0.027
Temp_shallow_June	0.224	-0.173
SC_deep_June	0.083	0.07
SC_shallow_June	0.374	0.025
Temp_deep_July	.472(**)	-0.062

Pearson's Correlation for DCA Plot	**Axis 1**	**Axis 2**
Temp_shallow_july	.566(**)	0.125
SC_deep_July	0.197	0.16
SC_shallow_July	0.178	0.07
Temp_deep_Aug	.425(**)	0.051
Temp_shallow_Aug	.319(*)	-0.045
SC_deep_Aug	-0.167	0.094
SC_shallow_Aug	-.285(*)	-0.014
**	Correlation is significant at the 0.01 level (2-tailed).	
*	Correlation is significant at the 0.05 level (2-tailed).	