

Hydrology, vegetation, and wet meadow restoration at Weippe Prairie, Nez Perce National Historical Park, Idaho



Photo credit: NEPE

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CONTENTS

Summary	1
Introduction	1
Methods.....	2
Hydrology.....	2
Soil Oxidation/Reduction.....	4
Vegetation composition.....	4
Soils	5
Camas - Hardpan relationship.....	5
Soil density profiles	5
Restoration of hydrology and vegetation	6
Results.....	8
Hydrology.....	8
Description of the hydrologic system	8
Hydrologic effects of restoration	9
Complimentary hand and data logger well measurements	11
Soil Oxidation/Reduction potential	12
Vegetation.....	13
Vegetation in the restoration planting zone.....	13
Vegetation composition in 2012.....	15
Vegetation composition in 2017 and differences from 2012	18
<i>Phalaris arundinacea</i> distribution.....	24
Soils	24
Soil density relationships to camas.....	24
Soil compaction from vehicle traffic during restoration.....	26
Discussion and Recommendations	27
References	28
Appendix A. Photos of the study and methods	30
Appendix B. Supplementary Figures	35

SUMMARY

The Weippe Prairie unit of Nez Perce National Historical Park serves to let visitors experience the setting encountered by Lewis and Clark when they first met the Nez Perce people. In the 1805 encounter the site was a wet meadow supporting camas lily (*Camassia quamash*) and other native wetland plants, but over the past two centuries the landscape has been heavily altered. Land use alterations included digging drainage ditches, plowing, and introducing exotic plant species. This report summarizes our work from 2011 to 2018 analyzing the hydrologic, soil, and vegetation conditions at Weippe Prairie. It also documents hydrologic and vegetation restorations and their effects on the landscape. Study methods included a network of monitoring wells and staff gauges to track water levels through time, soil oxidation/reduction stations to measure soil redox potential, characterization of soil physical properties, and vegetation analyses. In fall 2015 we permanently filled a drainage ditch with mineral sediment, which increased ponding, delayed runoff, raised the water level, and increased the duration of plant-available water through the growing season. Native wetland species were planted on the filled ground in 2016, and seedlings successfully expanded after two growing seasons. The prairie has not transitioned from dominance by exotic pasture grasses to a native wetland assemblage, but the area that was hydrologically restored and planted appears to be on a desirable trajectory. The larger landscape at Weippe Prairie still has several artificial drainage ditches that could be targeted for future restorations, actions that would both enhance visitor experience and improve the integrity of the wet meadow ecosystem.

INTRODUCTION

Wetlands are critical habitats in Idaho as they account for less than one percent of the land area yet support 75 percent of the state's wildlife for some part of their life cycle (Idaho Department of Fish and Game 1990, Fretwell et al. 1996). Wet meadows are seasonally saturated wetlands with mineral soils that provide critical habitat, ecological function, and cultural values. Weippe Prairie is one such wet meadow located in Nez Perce National Historical Park (NEPE).

Weippe Prairie is located in the Weippe Prairie Northern Rockies ecoregion, which is a gently sloping basalt plateau of mixed coniferous forest and shortgrass prairie that supports agriculture, grazing and logging (United States Department of the Interior 1997, McGrath et al. 2002). Weippe Prairie is an important historical site where the Nez Perce traditionally gathered for thousands of years to socialize, worship, and harvest the roots of camas (*Camassia quamash*). Weippe Prairie is also notable because it is where William Clark first met the Nez Perce on 20 September 1805 and was joined 4 days later by Meriwether Lewis and the rest of the Lewis and Clark Expedition party. They returned to the hospitable site and stayed for over a month on their return journey eastward in 1806.

During Caucasian settlement of the West, Weippe Prairie was homesteaded and modified by drainage features to improve cropping and grazing. The south unit at Weippe Prairie was altered by a large ditch that captured surface water from the wet meadow and took it north to Jim Ford Creek. The ditch diverted surface water and altered the sheet flow hydrologic processes that supported seasonally

saturated conditions and wetland plants, including camas. Land use changes and reduced saturation due to drainage no longer supported dense populations of native wetland plants, which coincided with the introduction of Eurasian pasture grasses and their proliferation for hay production. The National Park Service (NPS) goals for Weippe Prairie include returning the property to a more natural condition, which would have ecological benefits and enhance visitor experience by creating a setting more like that encountered by the Lewis and Clark Expedition.

Camas is a perennial lily that grows from an edible bulb and produces blue flowers from April to June (Stevens et al. 2000). It is considered one of the most important root foods of North American indigenous peoples and is recognized as a plant of considerable cultural and historical significance at NEPE. Camas is classified as a facultative wetland plant most commonly associated with seasonally wet meadows that are dry in summer. Camas is part of a community of wetland species whose habitat was a desirable restoration target at Weippe Prairie.

In 2011, we initiated a research project to characterize the hydrologic and vegetation composition at Weippe Prairie. The goals of the first phase were to identify indicators of past wetland conditions and to describe the hydrologic conditions and vegetation composition along a water level gradient. This information supported a pilot restoration phase where a drainage ditch was blocked with three plywood check dams. The hydrology was further evaluated, and results were used to plan the permanent infilling of the ditch for ecosystem restoration. Goals of the restoration were to reestablish hydrologic connectivity, remove reed canary grass stands along the ditch length, and plant native species seedlings into the ditch-fill to reestablish a wet meadow plant community. Two years after restoration, we evaluated its effects on seasonal water level dynamics, establishment of planted seedlings along the filled ditch, and vegetation composition across the prairie. Study goals were addressed by asking:

1. What is the relationship between surface water and groundwater at Weippe Prairie, and how did the ditch and its restoration affect hydrologic conditions?
2. How do land use history, soils, and hydrology influence plant species composition?
3. How did ditch filling and planting influence vegetation community structure?

METHODS

HYDROLOGY

To measure water levels on Weippe Prairie we installed 43 groundwater monitoring wells, 13 staff gauges, and 4 piezometers in October 2011. Water levels were measured in 2012, 2013, 2014, 2017 and 2018. Wells were constructed using hand slotted 1.5" inside diameter PVC pipe. Piezometers were constructed using 0.5" PVC pipes open only at the bottom. Staff gauges were t-posts installed in the ditches (i.e., manmade channels) and used to measure the depth of standing water. Most wells were completed to 45-65 cm below the soil surface, but they ranged from 25-114 cm depth. At eight well sites we installed 2 or 3 wells adjacent to each other and completed to different depths. These well nests were installed to help us to determine if deeper wells extended beyond a near surface confining layer and drained surface water and whether a water table existed in the soil.

In most years, pressure transducers recorded hourly water depth in nine wells and staff gauges. To broaden the spatial extent of hydrologic monitoring, NEPE staff manually measured water level in all instruments weekly from late-April through June, then approximately biweekly until wells were dry in late July through mid-September. Hand measurements were less-frequent but increased spatial resolution and allowed for interpolation across the landscape.

25 wells in the western portion of the southern prairie and five staff gauges in the ditch were used to assess hydrologic impacts from the ditch near the western property boundary before and after it was filled (Fig. 1). In 2012 we implemented a pilot project to block the ditch in three areas with temporary plywood dams, and the water level response was measured in 2013 and 2014. In October of 2015 the entire ditch was filled with sediment and the water level response was measured in 2017 and 2018. We also measured water levels in 18 wells in reference areas that were unaffected by the ditch or its restoration. Wells in the restoration area were in transects perpendicular to the ditch. Reference area wells were in two locations: the low-lying area along a ditch on the east side of the south prairie, and in a transect east of Jim Ford Creek on the north prairie (Fig. 1). Comparisons between restoration and reference wells allowed us to identify hydrologic effects of restoration.

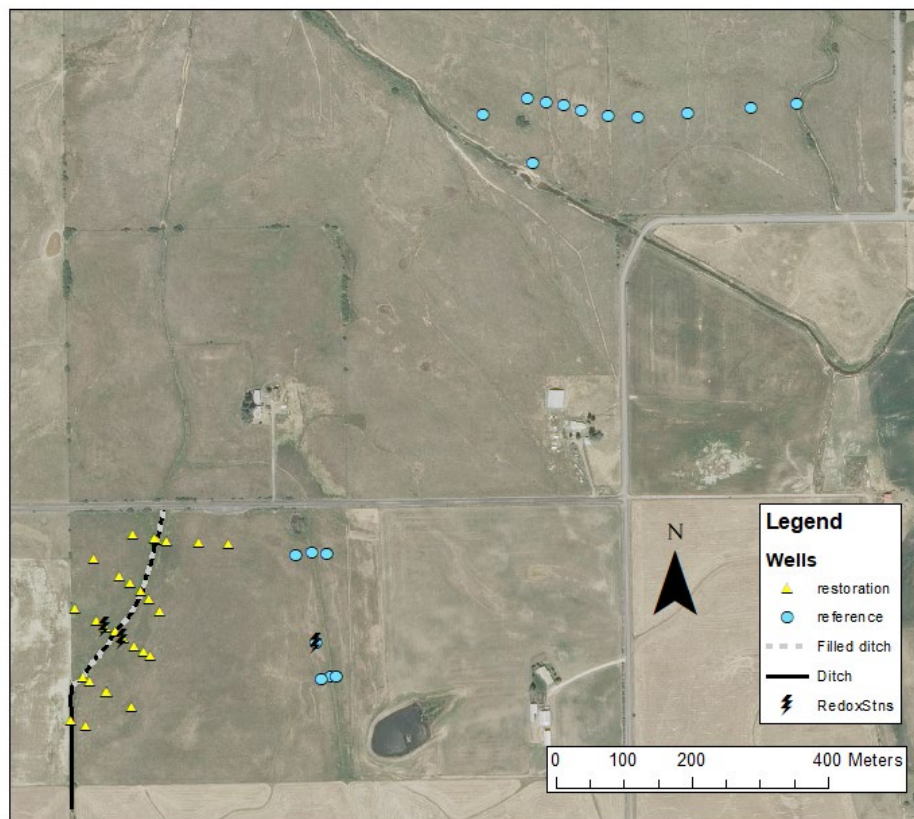


Figure 1. Aerial view showing location of instruments at Weippe Prairie, including wells, staff gauges, and redox stations. Yellow triangles are wells in the restored area and blue circles are reference area wells. The infilled ditch is the gray-black dashed line.

SOIL OXIDATION/REDUCTION

One goal of this research was to document if different areas across Weippe Prairie were truly wetlands. We assessed this question by measuring the soil oxidation/reduction (redox) potential at three sites in 2012 and 2013 (Fig. 1). Redox potential is a measure of the electron pressure in a solution, and it quantifies the degree of electrochemical reduction of soils. Reduction of chemicals occurs when they accept a hydrogen or electron, which occurs in the absence of oxygen. Redox values are commonly divided into four categories: oxidized ($> +350$ mV), moderately reduced soils ($+100$ to $+350$ mV), reduced (-100 to $+100$ mV), and highly reduced (-300 to -100 mV) (Batzer and Sharitz 2006). We consider sites to be oxic if their redox potential was $\geq +350$ mV and reducing if their redox potential was less than $+350$ mV.

We measured soil redox potential using pure platinum tipped electrodes. Each electrode was coupled with a Calomel reference electrode, and a Campbell Scientific data logger provided an impulse to both electrodes simultaneously and recorded the difference. We established three redox stations. Two were located to the east and west of the restoration ditch, and one was at a reference site on the east side of the south prairie (Fig. 1). At each station, four pairs of electrodes were installed at 20 cm depth and recorded hourly measurements. Persistence of anoxic conditions for at least two consecutive weeks during the growing season was used to determine if wetland hydrogeochemical conditions exist at each site.

VEGETATION COMPOSITION

Vegetation composition was analyzed around each monitoring well and along transects in 2012 and 2017. Canopy cover by species was visually estimated to the nearest 1% in a circular 1 m radius plot surrounding each well or 1 m² quadrats placed every 5 meters along established 25 to 50 meter transects. We analyzed 25 plots around wells and 46 transect quadrats. In 2012, vegetation composition was analyzed in mid-July at wells by David Cooper, and in transect quadrats by Tom Rodhouse, Devin Stucki, Dan Esposito, and Jannis Jocius on August 28-29. On July 31 and August 1, 2017, vegetation was analyzed around wells and in transect quadrats by Andrea Borkenhagen, Derek Schook, Heidi Becker, Katy Matthews, and Devin Stucki. A mid-May water level measurement from each well was used to compare site wetness during early summer. Water levels for well plots were obtained from the corresponding well whereas water levels for transect quadrats were determined through inverse distance weighting spatial interpolation of well data.

To evaluate plant establishment along the filled and revegetated ditch, vegetation was surveyed using the line intercept method. Starting 10 meters from the north culvert, a transect perpendicular to the ditch was established across the disturbed or newly placed soils. Transects were established every 10 meters for a total of 28 transects along the restored ditch length of 280 meters. The width of disturbance varied from 6 to 10 meters. Along each transect, the length each species touched the tape, and bare ground length was recorded to the nearest 5 cm. Percent cover of each species and bare ground was calculated by dividing the intercept measurements by the transect line length. Seedling size was a linear measurement along the transect.

A community matrix was generated using relative abundances of all species from each plot. Bray-Curtis similarity (Bray and Curtis 1957) resemblance matrix and a non-metric multidimensional

scaling ordination (NMDS) was used to construct a two-dimensional ordination representing floristic relationships among samples. A solution for the NMDS ordination was reached in 2 dimensions using the 2012 data after 49 iterations with a stress value of 0.15, and using the 2017 data after 99 iterations with a stress value of 0.13. Environmental factors were analyzed for their correlation to ordination results ($\alpha = 0.05$). Significant predictors vectors are shown in the ordination figures and scaled by the strength of the coefficient of determination (r^2). Groups of plots and quadrats with similar floristic composition were identified and termed communities using a flexible beta (-0.25) cluster analysis with a cut off level of $h = 1.2$ for 2013 and $h = 1.1$ for 2017. A similarity percentages analysis (SIMPER) identified the species contributing most to the similarities and differences between groups. All multivariate analyses were conducted in R v3.3.3 and SIMPER analysis was conducted in Primer v6 (Primer-E, Plymouth, UK; Clarke and Gorley 2015).

SOILS

Camas - Hardpan relationship

Soils provide the foundation for the Weippe Prairie wet meadow ecosystem. The soils are composed of silt and clay and are strongly acid (McDaniel and Falen 2011). They have very low permeability and a hydraulically-restrictive subsoil ~60 cm beneath ground surface (McDaniel and Falen 2011). This layer is a “hardpan” and is a caliche layer of very high density that appears to function as a barrier to surface and groundwater infiltration and creates perched free-water.

We tested the concept that camas abundance was correlated with hardpan depth using measures of soil and camas density. On April 25-26, 2013 we conducted a depth to hardpan survey across the north and south units of Weippe Prairie by pushing a soil probe into the ground until reaching a highly resistant layer. To verify that we consistently identified the hardpan, we augered a hole at eight locations adjacent to probed sites and examined the soil, and we found that the two methods produced very similar results. We established six transects that crossed areas of high and low camas density. Camas densities were determined from interpolation of the 2011 NEPE camas plots. Hardpan depth was measured along transects approximately every 15 m. After the third transect we recognized that camas density changed at a smaller scale than was captured by the 2011 camas density survey, so at the final three transects we assigned a value of 1 (low density) to 4 (high density) to each point. A seventh sampled area was a cluster of 20 points along the east side of the south prairie unit, which we termed a 7th “transect”. We used linear regression, one-way ANOVA, and Student’s t-tests to compare camas density to hardpan depth.

Soil density profiles

Dump trucks brought sediment to fill the western ditch, and the fill was compacted by bulldozers and excavators. The heavy machinery also incidentally compacted the intact prairie adjacent to the fill zone. We measured soil density in the work area to evaluate how the machinery affected soil compaction and the potential for plant growth. We 1) compared soil density of the imported fill zone to the reference prairie areas, 2) compared the soil density between the reference prairie and areas where it was repeatedly driven over, and 3) evaluated if soil density profiles change through time with saturation, freezing, and thawing.

Repeated measures of soil density were made from the ground surface to 45 cm depth using a Spectrum Technologies, Inc. FieldScout SC 900 soil compaction meter. The penetrometer measured density at 2.5 cm depth increments. After the October 2015 ditch filling, we established two transects perpendicular to the former ditch. The first transect started at well 25 and extended east toward well 29. The second transect began at the fencepost of the central redox station and extended east beyond the fencepost of the eastern redox station. Each measurement ($n = 70$) was made at a known distance along the transect, and all measurements were repeated in August 2017, after two winters, runoff seasons, and growing seasons. All measurements were classified into one of three zones: “reference” is prairie unaffected by the ditch filling, “fill” is newly deposited fill that is located in the former ditch, and “compacted” is area outside of the ditch fill that was driven on by heavy machinery.

RESTORATION OF HYDROLOGY AND VEGETATION

After measuring one growing season of baseline pre-restoration water levels in 2012, three plywood dams were installed across the western ditch in September 2012. This simulated the effect to the surrounding landscape that could result from complete ditch filling. Water levels in 2013 and 2014 reflect the effects of these dams, which were spaced 75 m apart. Dams pooled water, causing surface water to overtop them and flow outside of the ditch, where it pooled and created low-energy overland flow. The dams raised the water elevation in the ditch, decreasing the hydrologic gradient between the meadow’s near-surface groundwater and the ditch surface water.

In October 2015 a 300 m length of the ditch was filled with mineral sediment. The fill extended from the road culvert upstream (south) to the bend in the ditch at the western property boundary. Solid Rock Gravel performed the earthwork. Using an excavator, the bottom and sides of the ditch were cleaned of stands of *Phalaris arundinacea* (reed canary grass). The ditch edges were scraped to create level surfaces and prevent buried preferential flow paths at undercut banks. The excavated material was disposed off-site to reduce reed canary grass reinvasion potential in the newly placed soil. Local fine-grained mineral soil was placed in the ditch and compacted with a roller for stabilization and to reduce soil porosity. The fill was capped with 15 cm of weed-free local topsoil. The finished surface elevation was 4-8 cm above the surrounding prairie to allow for settling and discourage gully formation in the fill. Finally, the soil surface was raked with the dozer to create microtopography to aid planting. NEPE staff found the filled area to average 5.8 m wide over the 300 m length, leaving a total of 1800 m² of bare soil that was targeted for native seedling plantings.

Local native seed of target species was collected by CSU and NEPE staff in 2015. Intermountain Aquatics, Inc. propagated seeds in a greenhouse, and provided additional seed to fulfill planting needs. Species were selected based on local abundance in wet meadow reference ecosystems. In May 2016, NEPE staff and Intermountain Aquatics planted 9,100 seedlings of five species at a density of 4 seedlings/m² (Table 1). Planting zones along the ditch were determined based on relative elevations of the topography, which related to expected seasonal water levels (Fig. 2). The area was dividing into four zones and species were planted in overlapping zones in rough accordance with their hydrologic preferences.

Table 1. Species and seedling numbers to be planted at Weippe Prairie.

Plant species	Common Name	Container type	Seedling number	Percent of total (%)	Planting zones
<i>Carex vesicaria</i>	Blister Sedge	5.5 cubic inch	320	3.5	D
<i>Carex nebrascensis</i>	Nebraska Sedge	5.5 cubic inch	28	0.3	B-C
<i>Carex microptera</i>	Smallwing Sedge	5.5 cubic inch	2,240	24.6	C-D
<i>Scirpus microcarpus</i>	Panicled Bulrush	5.5 cubic inch	640	7	A
<i>Carex pellita</i>	Woolly Sedge	5.5 cubic inch	9	0.1	A-D
<i>Carex pellita</i>	Woolly Sedge	Bare Root	5,863	64.4	A-D
Total			9,100		

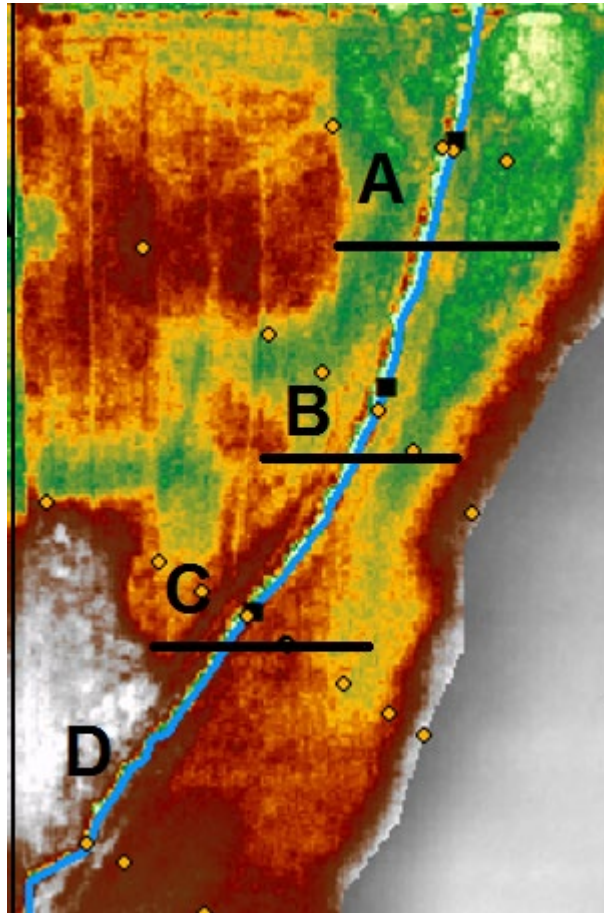


Figure 2. Restoration area elevation and planting zones. Ditch is blue line, black lines indicate transitional changes in elevations, and letter indicate planting zones. Color gradient shows elevation from white-red (high) to green-blue (low).

RESULTS

HYDROLOGY

Description of the hydrologic system

Weippe Prairie is a seasonally-saturated wet meadow that retains water from winter and spring precipitation near the ground surface through early summer. The low permeability soil promotes sheet flow early in the growing season (April to early June), and the drainage ditches across the prairie serve to artificially dewatered the area. Water can seasonally be found near the ground surface atop the very low-permeability confining layer that is generally found within 60 cm below ground. Well data revealed near-surface free water from snowmelt in late April through May or early July. After early summer, precipitation decreases, transpiration increases, and drainage promoted by the ditches dried the landscape.

Water levels during 2018 from example well 28, which was equipped with a logging pressure transducer, illustrate that the near-surface water disappears abruptly (Fig. 3; wells are located by number in Fig. 5, below). Standing water occurred through late June, but in early July the water level declined by 39 cm in three days. Because the topographic gradient and transpiration demands of the site suggest a slower decline than 13 cm/day, this precipitous decline indicates that the water was saturated near the ground surface, but areas below the surface were unsaturated. After surface water inputs were exhausted, the water in the monitoring well quickly infiltrated the soil and the well went dry. The hydrologic system crossed a threshold when drainage surpassed inputs and retention, after which it no longer supported the perched water. Even though we did not capture the re-wetting period that happens over winter, this site and surrounding areas on the prairie clearly do not support a typical water table in the soil that is wetted from the bottom up. Water retention is vital for vegetation in areas that receive little growing season rain. Therefore, artificial drainage that reduces surface flooding can severely impair an ecosystem. Our interpretation of the hydrologic system is like that provided by McDaniel and Falen (2011, 2014) and Rockefeller et al. (2004).

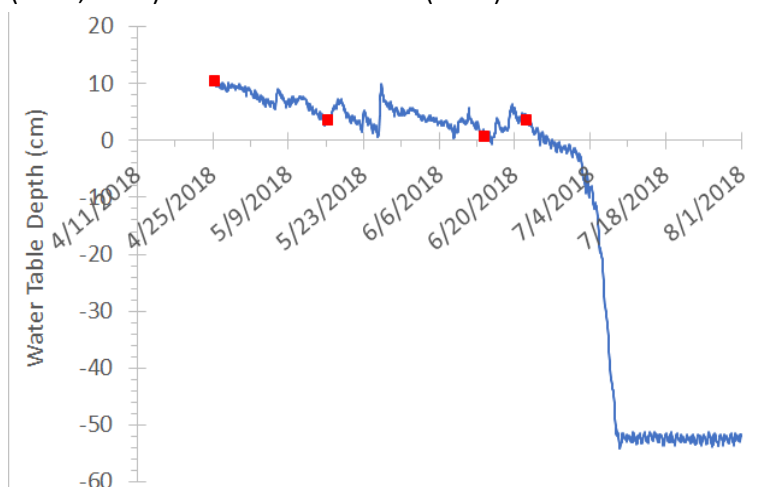


Figure 3. Water level in Well 28 in 2018 recorded by a groundwater logger (blue line) and hand measurements (red squares). Note that the flat portion of the blue line at the end represents a dry well.

Hydrologic effects of restoration

The ditch filling resulted in higher and more prolonged near-surface water levels, which in the long term will be favorable to the native wet meadow vegetation. Both the temporary plywood dams and subsequent complete ditch filling raised the water level throughout an area, and the effects extended at least 86 m from the ditch.

2012 reflected the pre-restoration groundwater conditions, 2013-2014 reflected hydrologic effects of the temporary plywood dams, and 2017-2018 data reflected water levels after permanent ditch filling. Nine data loggers recorded water levels at a subset of monitoring wells during the measurement years (2012, '13, '14, '17, and '18) including five wells with four or five years of measurements, three in the restoration area and two in reference areas. These five wells indicated that ditch restoration increased the height and duration of the near-surface water level. The baseline year 2012 had more summer rain than any of the five post-restoration measurement years (Fig. 4a), which partially obscured identification of treatment-induced effects. However, the restoration changes were significant enough to emerge regardless. For example, reference wells had late April through early May water levels higher in 2012 compared to 2018 (Fig. 4c). However, for restoration area wells including Well 12 (Fig. 4d), 2012 had the lowest recorded early summer water level of any year, opposite of reference wells. Well 17 within the restoration area but further from the ditch and slightly uphill from well 12, had an early summer water level height that was similar across years. This intermediate position suggests a reduced effect of restoration-induced water level impacts at increased distance and elevation above the ditch.

Water level logger data also revealed a second period in the growing season having treatment effects from ditch filling. For all dates after May 23rd, the highest water levels in reference wells occurred in 2012. For wells in the restoration area, however, 2012 was the wettest year after May 23rd for only 10-12 days following rain events (logger data from Wells 10, 12 (Fig. 4d), and 17). Using 2012 data as a reference level revealed that the 2013-2018 restoration area had higher water levels relative to the baseline. The water level dataset indicates that the ditch filling achieved the desired effects of slowing runoff, prolonging saturation, and extending the duration of growing season plant-available water.

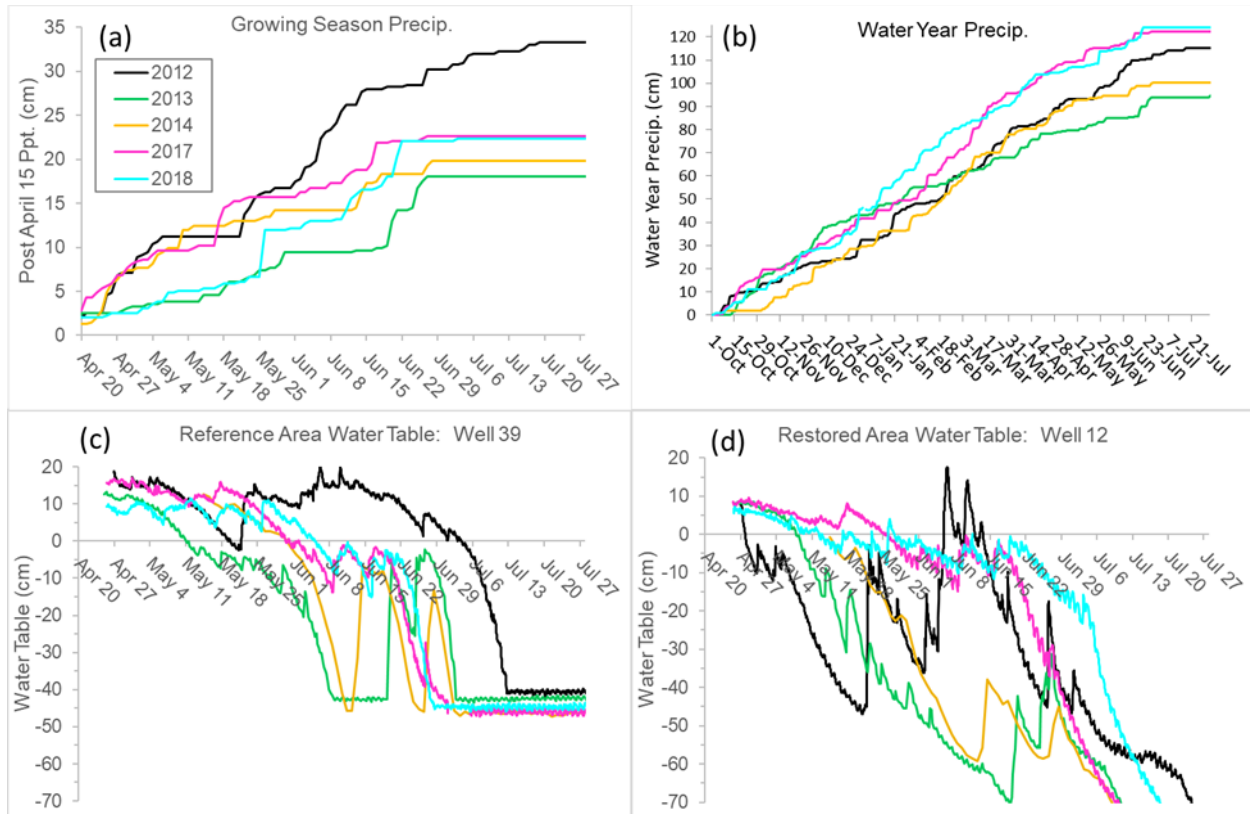


Figure 4. (a) Growing season (Apr 15 - Jul 31) and (b) water year (Oct 1 – Sep 30) precipitation for study years 2012-2018. Growing season water levels are shown for example (c) well 39 in the unrestored reference area and (d) well 12 the restored ditch area. 2012 (black line) is pre-restoration water level and shows baseline water levels unaffected by restoration. 2012 had the highest summer rain (a), but precipitation was average for the entire water year (b), while years 2017 and 2018 had average summer but high water year precipitation. The relative positions of the pre-restoration 2012 water level in reference vs. restored zones: (c) for the reference area 2012 was highest for most of the season, but (d) shows that the dams raised the early-season water level in 2013 and 2014 but did not maintain high water as long as the ditch filling restoration (2017-2018). Note that the roughly horizontal data at bottom in (c) means the well was dry. Three more wells are shown in Appendix B (Fig. B3).

Water levels were similar in May of 2012 and 2017 for the reference wells. The 18 reference wells had an average water level only +2.5 cm higher on May 9, 2017 compared to May 11, 2012 (standard error = 0.8 cm; range = -8 to +7 cm). This very small difference provided ideal dates for assessing the hydrologic effects of the restoration. For these same dates, the water level in restoration area wells averaged 25.8 cm higher in 2017 than 2012 (standard error = 1.6 cm; range = +6 to +32 cm; Fig. 5). Wells located near each other in the restoration area had similar water level variation during the study, allowing water level interpolation between wells to estimate a continuous water surface. This surface revealed that water level increases were greatest near the filled ditch, and smaller with distance from the ditch (Fig. 5).

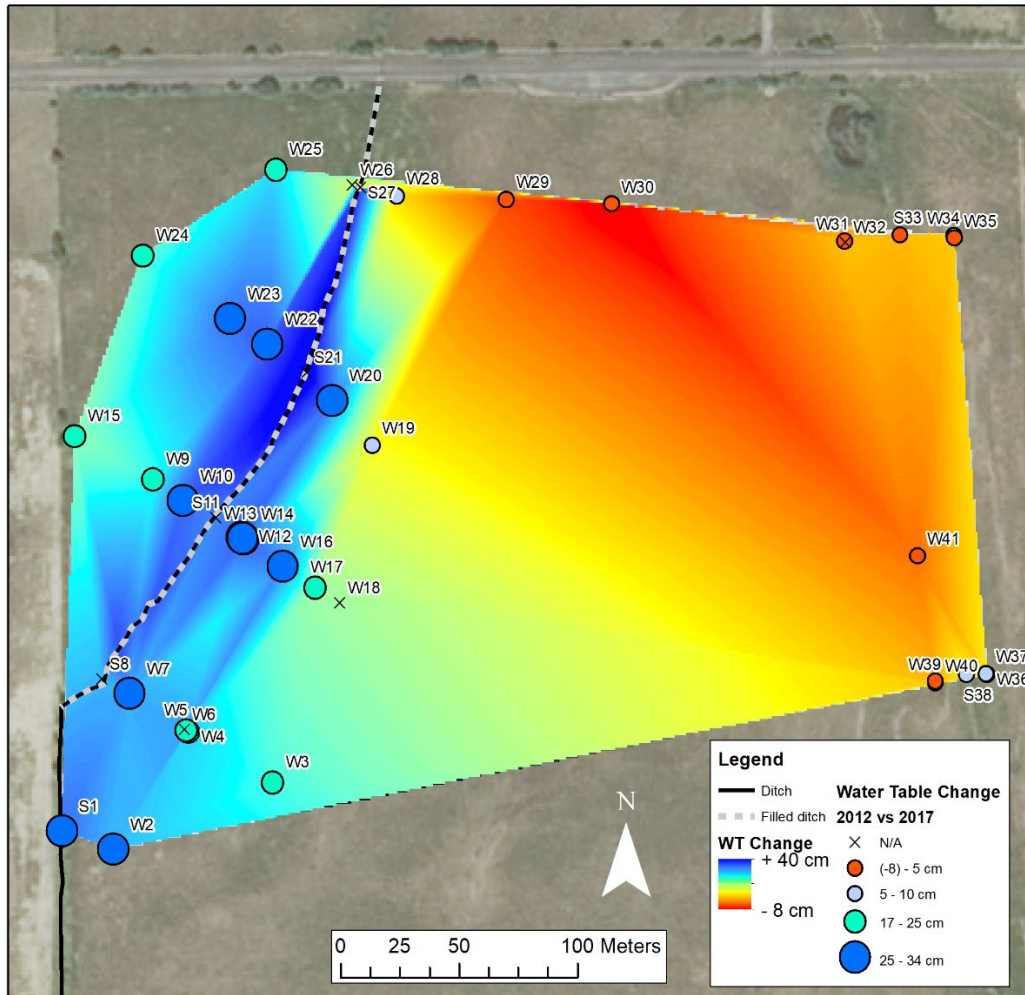


Figure 5. Water level elevation differences between May 11, 2012 and May 9, 2017. Circles identify wells with measurements from both dates. Circles are scaled to magnitude of change, with small red circles having little change and large blue circles being roughly 30 cm higher in 2017. The red-blue surface interpolates water level changes, which range from little change (red) up to a 40 cm increase (blue). Note the contrast between the restored ditch (dashed line) at left and the reference area on the right where no restoration occurred.

Complimentary hand and data logger well measurements

NEPE staff measured water level depths in the 52 wells and staff gauges between 2012-2018. In each study year up to nine wells had data loggers recording water level depth every 1- to 6-hours. Hand and logger measurements complemented each other and contributed to our understanding of water levels through time. Logger measurements had higher temporal resolution, which was essential for understanding rapid water level changes and the timing of water loss during the summer (Fig. 6). Hand measurements increased the spatial resolution of water level data, allowing wider inferences and interpolation between wells. Additionally, the datasets complimented each other because hand measurements were used to validate the logger data, allowing the correction of data where needed. For example, the logger data from Well 10 in 2013 deviated substantially from hand measurements, so the logger was identified to have malfunctioned and the data were discarded. We also used the hand-

measurements to calibrate logger data. For example, if hand measures were consistently 2-3 cm lower from logger measurements within a well, the logger dataset for that series was shifted down by 2.5 cm. This accounted for errors introduced when hanging loggers or small errors in the pressure sensor.

An interesting result of this hydrologic analysis is that relatively small summer rain events resulted in a large water level rise, surface water ponding, and sheet flow that extends the duration of the wet season. It is also clear that the near-surface water is not connected to regional groundwater. Water is either perched near the surface or the sites are dry. The deeper drawdown recorded by loggers such as in late June 2017 (Fig. 6) is likely due to surface water filling the well, and once surface water is no longer present the well water infiltrates the soil.

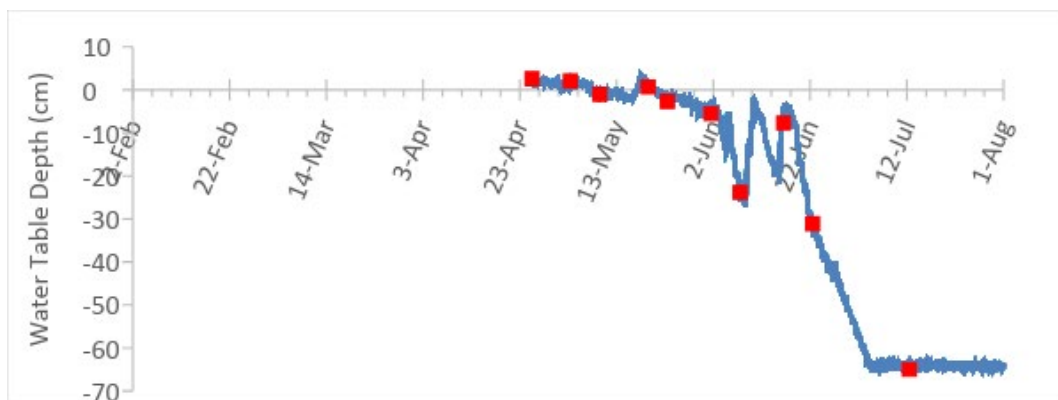


Figure 6. Example of hand measurements (red squares) compared to logger measurements (blue line) for Well 10 in 2017. Weekly hand measurements accurately captured water level changes in early summer, but they missed the water level dynamics between June 9 and June 17. Hand measurements also did not identify the well as “dry” (-65 cm) until July 12, seven days after the logger did.

SOIL OXIDATION/REDUCTION POTENTIAL

The soil redox potential indicated that anoxic conditions occurred at all three measurement sites in early summer of both study years (Fig. 7). At well 10, located along the drainage ditch, the redox potential was below 350 mV, the boundary between oxidized and anoxic conditions, when the water level was within 20 cm of the soil surface. At well 12, also near the ditch, the redox potential remained low from early May 2012 through June 2012. Redox potential varied with water level as the prairie wetted and dried in June, but it did not become oxic until early July. The reference site, well 41, had a water level near the soil surface until early July and the redox potential was below 300 mV until that time indicating long duration anoxic soil conditions. During 2013 the soil remained anoxic until late May, a shorter period of anaerobic conditions than in 2012. Significant early summer precipitation in 2012 helped maintain water levels near the surface, while in 2013, there was little early summer precipitation and water levels dropped. Changes in soil saturation and aeration were closely followed by changes in soil redox potential, which became anoxic when the soil within 20 cm of the soil surface was saturated. These data indicate that all three areas of Weippe Prairie had anoxic soils early in the growing season for a sufficient length of time (at least two consecutive weeks) to create wetland hydrology conditions.

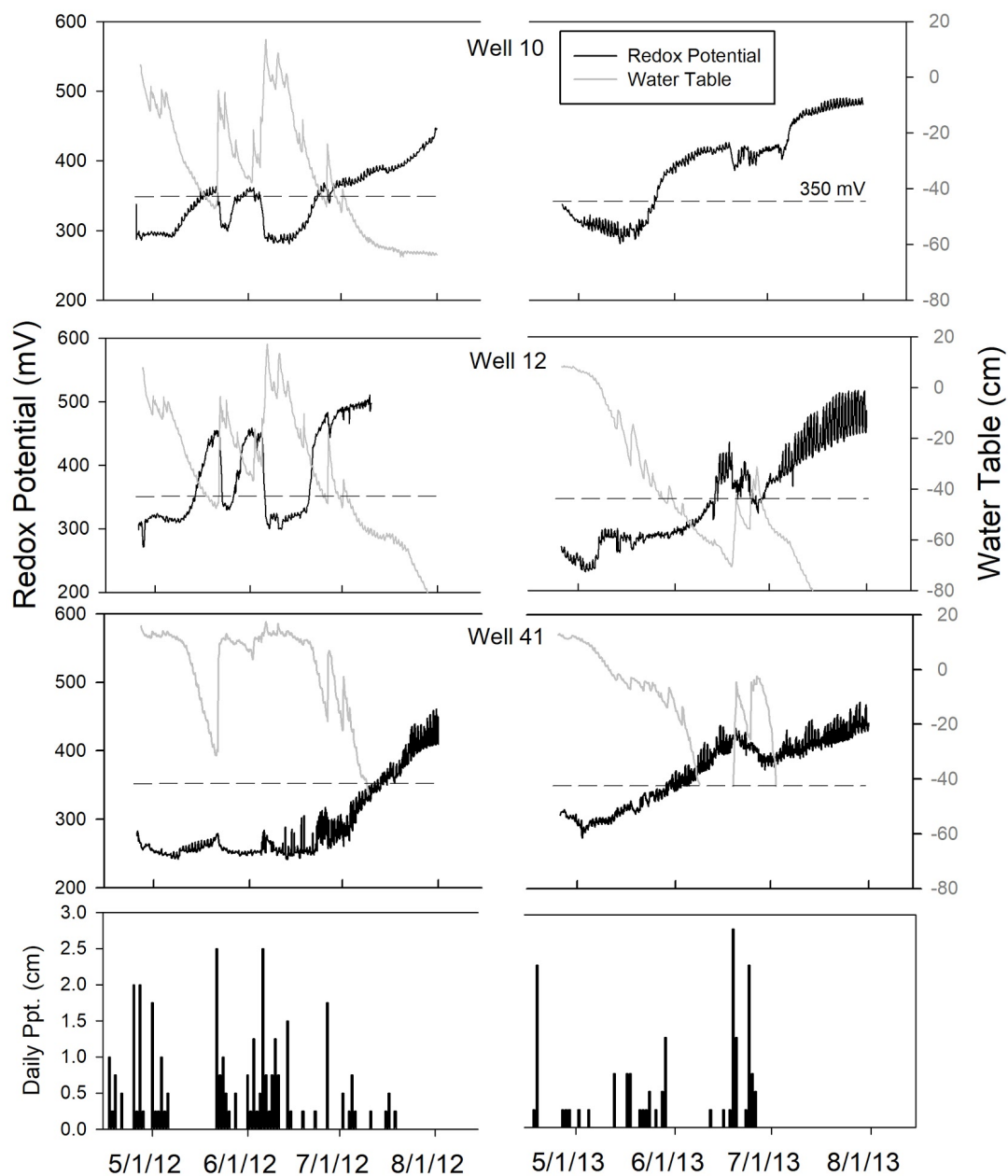


Figure 7. Water levels, redox potential, and precipitation at three locations of Weippe Prairie, 2012 and 2013. The top two panels are from locations along the restored ditch. Well 41 (third panel) is in a reference area on the prairie's eastern side in an area of high camas density.

VEGETATION

Vegetation in the restoration planting zone

Native wetland vegetation was planted in the ditch fill in early summer 2016. In July 2017, after two growing seasons, the relative cover of planted species averaged 13% of the ditch fill (standard error

(se) = 1 %; max = 25%, min = 1%, Fig. 8). Planted species varied in abundance and occurrence along the ditch-fill in accordance with the intended planting zones. *Carex pellita* was the most abundant species planted (64% of total seedlings) and occurred along the entire length of the ditch-fill. In 2017, it was 50% of total planted species cover and had an average seedling length of 23 cm along the sampled transects (se = 1.9, n = 68). *Carex microptera* was the second most abundant species planted (25% of total seedlings) and occurred near the southern end of the ditch-fill. It was 22% of total planted species cover and had an average seedling length of 37 cm (se = 5.1, n = 31). *Scirpus microcarpus* seedlings were 7% of total seedlings planted yet comprised 24% of total planted species cover with an average seedling length of 46 cm (se = 5.1, n = 25). *Carex vesicaria* was 3.5% of total seedlings planted and was 4% of total planted species cover, occurring near the fence with an average seedling length of 47 cm (se = 6.1, n = 6). A few *Carex nebrascensis* seedlings were planted (0.3% of total seedlings) but this species was not recorded during the survey.

Total plant relative cover averaged 77% (se = 2%) across the 28 transects along the ditch-line where fifteen species were recorded. The most abundant opportunistic species to establish in the ditch-fill were *Agrostis exarata* (avg. = 12%, se = 2%, max = 37%) and *Juncus bufonius* (avg. = 12%, se = 2%, max = 35%) (Fig. 8). Plant species with the highest relative cover varied by transect. *Agrostis exarata* had the highest relative cover of recorded species (16 - 37%) in 7 transects, *Juncus bufonius* (14 - 35%) in 6 transects, *Alopecurus pratensis* (20 - 27%) and *Phalaris arundinacea* (18 - 28%) in 5 transects, *Scirpus microcarpus* (17 - 23%) in 2 transects, and *Carex microptera* (23%), *Trifolium repens* (26%), and *Juncus ensifolius* (21%) in 1 transect each. One year after filling the ditch and planting seedlings (4/m²), the relative cover of bare ground averaged 23% (se = 2%) across the ditch-fill, with the highest proportion of bare ground occurring 140 - 220 m from the road.

The distribution of opportunistic species varied along the ditch-fill (Fig. 8). *Eleocharis palustris*, *Elymus trachycaulus*, *Juncus bufonius*, *Juncus ensifolius*, *Phalaris arundinacea*, and *Trifolium repens* had higher cover closer to the road (distance 0 m). The abundance of *Agrostis exarata*, *Alopecurus pratensis*, and *Carex stipata* was higher along transects farther from the road (distance 280 m). *Alisma plantago-aquatica* and *Juncus tenuis* cover did not differ along the ditch-fill. Of the opportunistic species to establish, *Agrostis exarata* was most abundant and the most desirable. It is a native perennial bunchgrass that occurs in a wide variety of habitats from wet meadows to uplands (Esser 1994). *Agrostis exarata* is considered a pioneer species known to colonize recently disturbed sites and remain important in early seral stages (Klinka et al. 1985). *Juncus bufonius* is an annual pioneer species that is typical on moist soils along meadows, stream banks, or roadsides. Following restoration, *J. bufonius* is desirable because it can rapidly establish to stabilize the soils and will not compete with the establishment of later successional species.

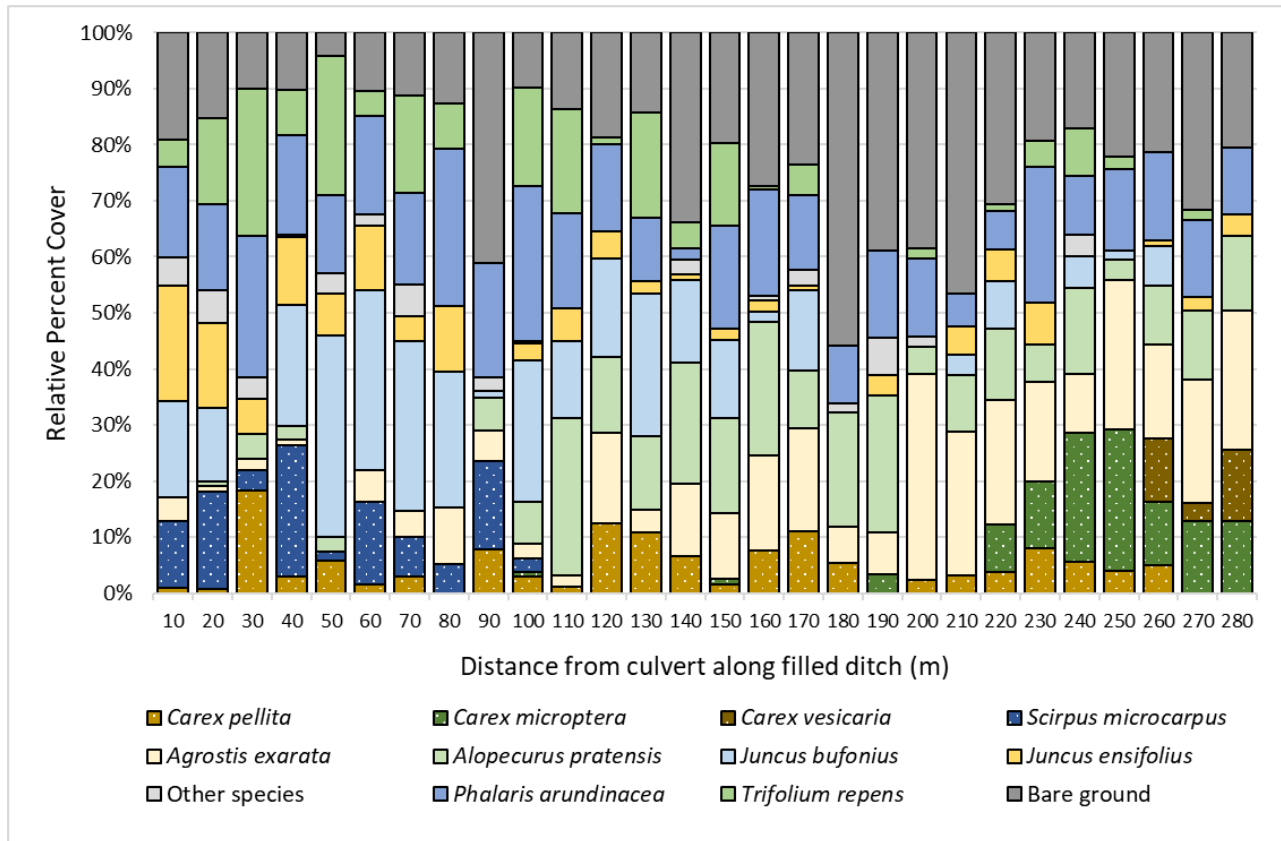


Figure 8. Relative percent cover of planted and opportunistic species and bare ground along the ditch-fill transect. Transect starts at the culvert (0 m) and runs to the southern end by the fence (280 m). Cross transects were surveyed every 10 m spanning the disturbed area across the ditch-fill. Species that were planted during restoration are indicated by darker stippled colors at the bottom of the figure.

Vegetation composition in 2012

In 2012, 43 species occurred in five plant communities that were identified using cluster analysis. Communities were characterized by the six letter codes of the top one or two species contributing the greatest proportion of within-community similarity (Table 2). The plots ordinated along the two major NMDS (ordination) axes, corresponding to water level and *Camassia quamash* cover (Fig. 9 and Table 2). The most abundant community was Alopra, which had the highest within group similarity, was dominated by *Alopecurus pratensis*, and occurred at an average May 2012 water level of -13 cm relative to ground surface (se = 3.0; Fig. 10). The second most common community was Phlpra-Alopra, dominated by *Phleum pratense* and *A. pratensis* and occurred at the average water level of -29 cm (se = 2.7). The Broine-Poacom community occurred at the deepest water level (avg. = -37 cm, se = 3.4) and the Alopra-Astsp. community had the highest species richness contributing to the average within group similarity. The Phaaru community was dominated by *P. arundinacea* and occurred where the May water level was closest to the surface but was the most variable within group (avg. = -7 cm, se = 6.2).

Table 2: Results from the Similarity Percentage analysis (SIMPER) of vegetation plots sampled in 2012. Showing the highest contributory species in abundance to the similarity within communities and the number of plots in each community (n). Includes average abundance (Av. Abund), average similarity (Av.Sim), similarity over standard deviation (Sim/SD), percent contribution (Contrib%), and cumulative contribution (Cum.%).

Community name	Average similarity	Species	Average Abundance	Average Similarity	Sim/SD	Contrib%	Cum.%
Alopra (n=23)	82.93	<i>Alopecurus pratensis</i>	86.59	80.74	9.02	97.36	97.36
Phlpra-Alopra (n=16)	47.2	<i>Phleum pratense</i>	44.79	33.22	2.26	70.38	70.38
		<i>Alopecurus pratensis</i>	21.07	10.54	0.84	22.32	92.7
Alopra-Astsp. (n=12)	39.14	<i>Alopecurus pratensis</i>	36.03	27.49	2.09	70.25	70.25
		<i>Aster species</i>	13.75	2.99	0.31	7.65	77.9
		<i>Phleum pratense</i>	9.2	2.86	0.45	7.3	85.2
		<i>Agrostis gigantea</i>	10.5	2.81	0.42	7.19	92.39
Broine-Poacom (n=12)	56.41	<i>Bromus inermis</i>	53.03	43.07	3.73	76.35	76.35
		<i>Poa compressa</i>	20.68	9.45	0.75	16.75	93.1
Phaaru (n=8)	68.23	<i>Phalaris arundinacea</i>	79.32	66.15	3.14	96.96	96.96

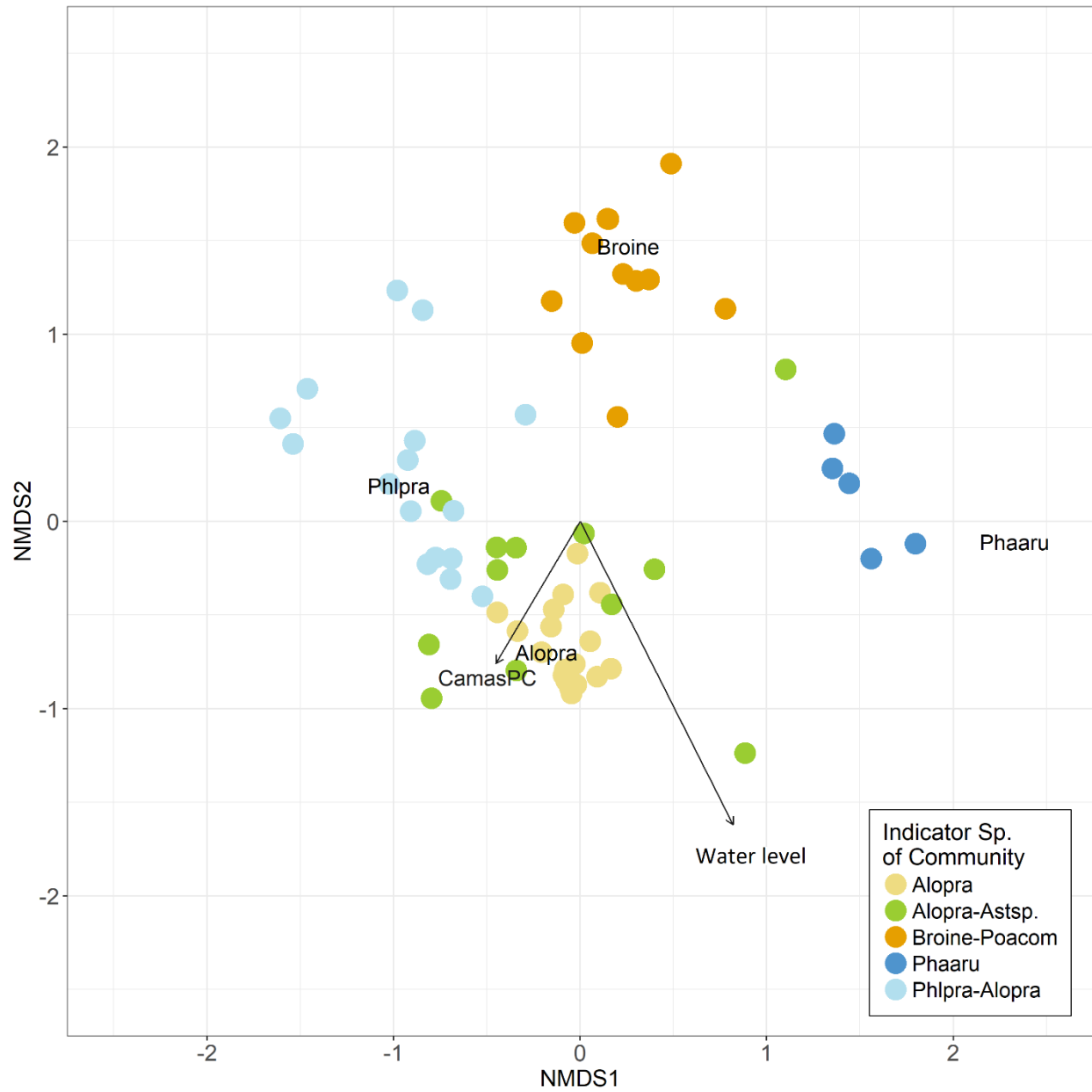


Figure 9: Non-metric multidimensional scaling (NMDS) ordination of plots sampled in 2012. Colors indicate communities determined by flexible beta cluster analysis and classified by the species that contributed the greatest proportion of similarity within groups, as determined by SIMPER analysis. Environmental variables of water level and *Camassia quamash* percent cover (CamasPC) are shown as vectors and were determined to be significantly correlated to projected plots. Presented species are dominant and show their distribution relative to communities (Broine = *Bromus inermis*, Phaaru = *Phalaris arundinacea*, Alopra = *Alopecurus pratensis*, and Phlpra = *Phleum pratense*).

Table 3: Fit of environmental variable vectors and their correlation coefficients to the NMDS ordination for 2012 data. Bolded P-values values are significant at $\alpha = 0.05$. Coordinates on NMDS1 and NMDS2 axes are for the heads of unit length vectors that are scaled by their coefficient of determination (r^2).

Environmental Vectors	NMDS1	NMDS2	r^2	P-value
Water level in May 2012	0.8576	-1.6200	0.4208	0.001
<i>Camassia quamash</i> percent cover	-0.4685	-0.7658	0.1003	0.026

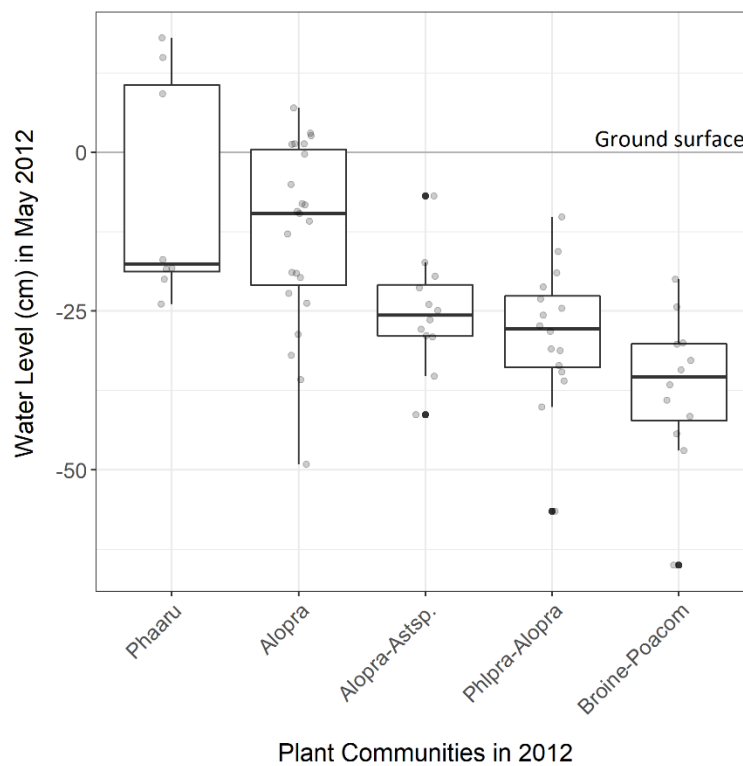


Figure 10: Depth to water level (cm) in May 2012 of plots within plant communities identified from similarity, ordination, and SIMPER analysis.

Vegetation composition in 2017 and differences from 2012

In 2017, 79 species were identified and seven plant communities were determined using cluster analysis. The communities were characterized by the six letter codes of the top one or two species that contributed the greatest proportion of within community similarity (Table 4). The plots ordinated along the two major NMDS axes with May water level being the only significant environmental variable (Fig. 11 and Table 5). Like 2012, the most common community was Alopra, which also had the highest within group similarity but occurred at a lower average May water level of 5 cm (se = 1.7; Fig. 12). The second

most common community was Alopra-Phaar, which was dominated by *A. pratensis* and occurred at the average May water level of -9 cm (se = 4.0). The average dissimilarity data was used to differentiate the Alopra and Alopra-Phaar communities because *A. pratensis* was the only species contributing to within group similarity. Dissimilarity comparisons indicated that the second most common species within the Alopra-Phaar community was *P. arundinacea* with an average abundance of 8.9%. A Phaaru community dominated by *P. arundinacea* occurred in plots with the most ponded water in May (avg = 8 cm, se = 3.1). Drier communities of Broine-Poacom and Phlpra-Forb occurred at the lowest May water levels in 2017 (avg = -17 cm, se = 4.8; and avg = -13 cm, se = 12). The Junbuf-Junens and Gnapal communities represent the ephemeral annual plants establishing along the ditch-fill area.

Table 4: Results from the Similarity Percentage analysis (SIMPER) of vegetation plots sampled in 2017. Showing the highest contributory species in abundance to the similarity within communities and the number of plots in each community (n). Includes average abundance (Av.Abund), average similarity (Av.Sim), similarity over standard deviation (Sim/SD), percent contribution (Contrib%), and cumulative contribution (Cum.%). The Alopra-Phaaru and Alopra communities both have only *Alopecurus pratensis* as the species that contributes to within community similarity, however, *Phalaris arundinacea* (Phaaru) contributed to the dissimilarity so was included to differentiate between the two communities.

Community name	Average similarity	Species	Av. Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Phaaru (n=10)	63.95	<i>Phalaris arundinacea</i>	70.17	58.55	3.83	91.56	91.56
Alopra-Phaaru (n=17)	60.07	<i>Alopecurus pratensis</i>	60.58	54.82	5.97	91.25	91.25
		<i>Phalaris arundinacea</i>	8.88	NA	NA	11.65	59.21
Alopra (n=27)	96	<i>Alopecurus pratensis</i>	96.99	95.41	36.52	99.39	99.39
Gnapal (n=3)	76.14	<i>Gnaphalium palustre</i>	80.18	70.08	106.8	92.04	92.04
Junbuf-Junens (n=3)	10.28	<i>Juncus bufonius</i>	28.72	6.58	1.13	63.96	63.96
		<i>Juncus ensifolius</i>	2.23	1.43	1.35	13.92	77.89
		<i>Gnaphalium palustre</i>	2.72	0.84	22.32	8.19	86.08
		<i>Eleocharis</i> species	4.85	0.55	0.58	5.32	91.39
Broine-Alopra (n=7)	74.4	<i>Bromus inermis</i>	72.88	65.88	7.13	88.55	88.55
		<i>Alopecurus pratensis</i>	7.04	3.82	1.63	5.14	93.69
Phlpra-Forb (n=4)	17.58	<i>Phleum pratense</i>	22.62	6.21	0.55	35.33	35.33
		Unk Forb	27.15	6.1	0.41	34.68	70.01
		<i>Alopecurus pratensis</i>	8.1	2.74	0.47	15.59	85.6
		<i>Bromus inermis</i>	5.96	1.41	0.41	8.03	93.64

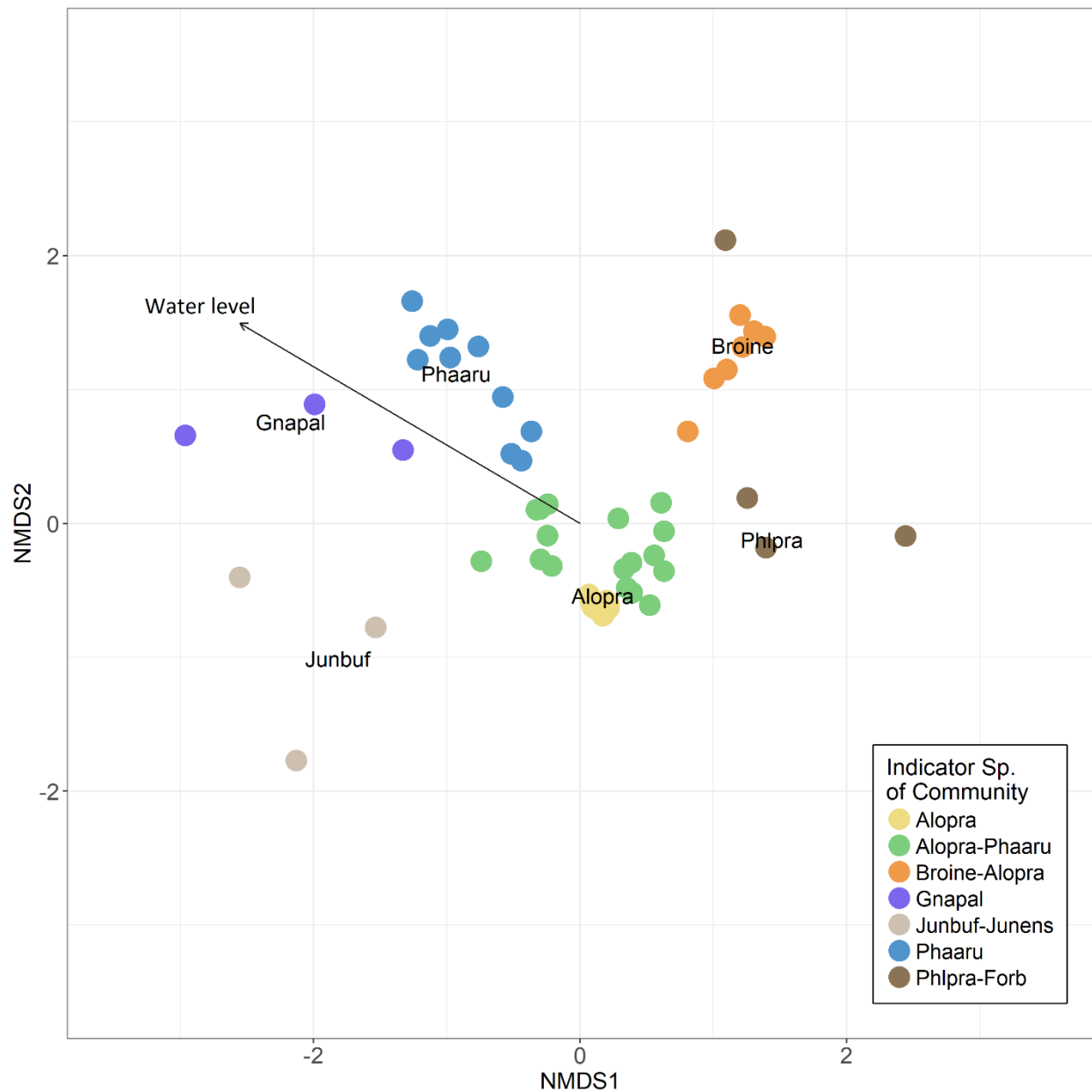


Figure 11: Non-metric multidimensional scaling (NMDS) ordination of plots sampled in 2017. Colors indicate communities determined by flexible beta cluster analysis and classified by the species that contributed the greatest proportion of similarity within groups, as determined by SIMPER analysis. Water level is shown as a vector and was determined to be significantly correlated to projected plots. Presented species are dominant and show their distribution relative to communities (Broine = *Bromus inermis*, Phlpra = *Phleum pratense*, Alopra = *Alopecurus pratensis*, Junbuf = *Juncus bufonius*, Gnapal = *Gnaphalium palustre*, and Phaaru = *Phalaris arundinacea*)

Table 5: Fit of environmental variable vectors and their correlated to the NMDS ordination of 2017 data. Bolded P-values are significant at $\alpha = 0.05$. Coordinates on NMDS1 and NMDS2 axes are for the heads of unit length vectors that are scaled by their coefficient of determination (r^2).

Environmental Vectors	NMDS1	NMDS2	r^2	P-value
Water level in May 2012	-2.9232	1.3865	0.1686	0.003
<i>Camassia quamash</i> percent cover	-0.5789	0.5313	0.0099	0.536
Water level change from May 2012 to 2017	0.7513	1.6200	0.0514	0.156
Average soil density from 5 to 10 cm depth	0.7246	-0.1509	0.0088	0.752

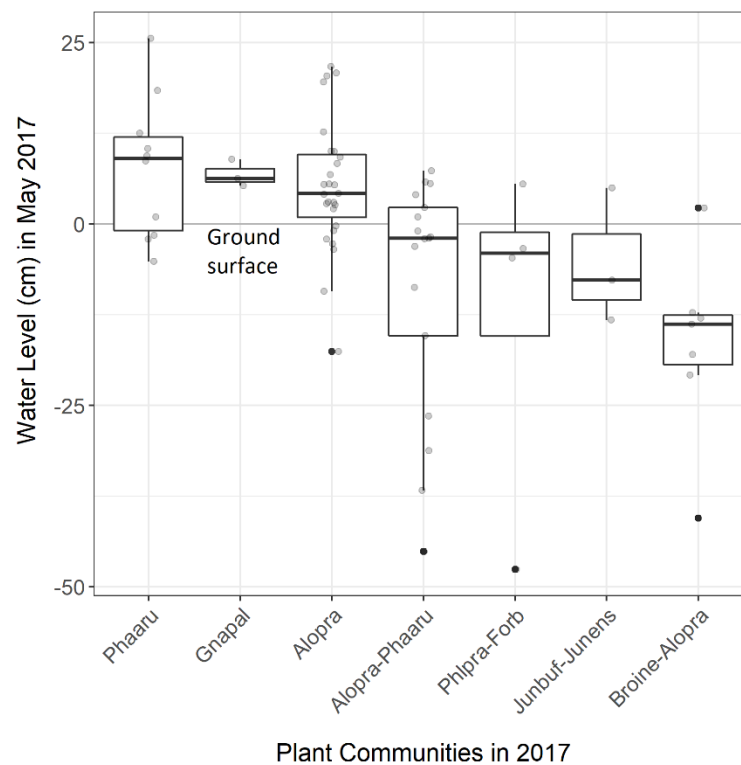


Figure 12: Depth to water level (cm) in May 2017 of plots within plant communities identified from similarity, ordination, and SIMPER analysis.

The number of plots that shifted community types from 2012 to 2017 varied by community (Fig. 13). Those that did not shift were in the Alopra and Phaaru communities. 75% of the 2012 Phaaru plots remained as the Phaaru community in 2017. 57% of the 2012 Alopra community plots remained as Alopra community in 2017. Convergence between these communities occurred as 17% of the 2012

Alopra plots and 25% of 2012 Phaaru plots become Alopra-Phaaru communities in 2017. Of the 2012 Alopra-Astsp., 42% became Alopra or Alopra-Phaaru and 50% of the 2012 Broine-Poacom plots became Broine-Alopra community in 2017. A complete shift in species composition from 2012 to 2017 occurred most notably in the 2017 Gnapal and Junbuf-Junens communities, which were influenced by the ditch-fill and also had the highest cover of native species. Across all vegetation plots and communities, native plant absolute cover increased from 6% (se = 1.1) in 2012 to 8% (2.3) in 2017 and exotic plant absolute cover decreased slightly from 76% (se = 2.4) to 73% (se = 4.0).

Camassia quamash is a target native species for restoration in Weippe Prairie. It was recorded in 41 of 71 plots in both 2012 and 2017, 27 of which were the same plots. In 2012, *C. quamash* cover ranged from 1 to 20% and averaged 2.6%. In 2017, where present its cover ranged from 1 to 70% and averaged 3.3%. The difference was slight and the average cover across all plots was comparable between years but more variable in 2017 (avg. in 2012 = 1.5%, se = 0.3%; avg. in 2017 = 1.9%, se = 1.0%). *Camassia quamash* was recorded in plots where the May water level was +7 cm to -57 cm from the soil surface in 2012 (avg. = -22 cm) and +21 cm to -45 cm in 2017 (avg. -2 cm). The highest cover occurred in plots where May water levels were approximately +10 cm to -10 cm from the soil surface. *Camassia quamash* cover was not related to the cover of other species but did have total plant cover averaging 91%, indicating gaps in the plant canopy. *Camassia quamash* propagates from seeds or bulbs and prefers full sun to partial shade. Targeted plantings within the water level range described above and where dense vegetation would not compete for light or belowground space could be successful (Stevens et al. 2000). However, the occurrence of *C. quamash* within the Weippe Prairie does provide a seed source and the post-restoration return of habitat with higher water levels may promote their increase over time.

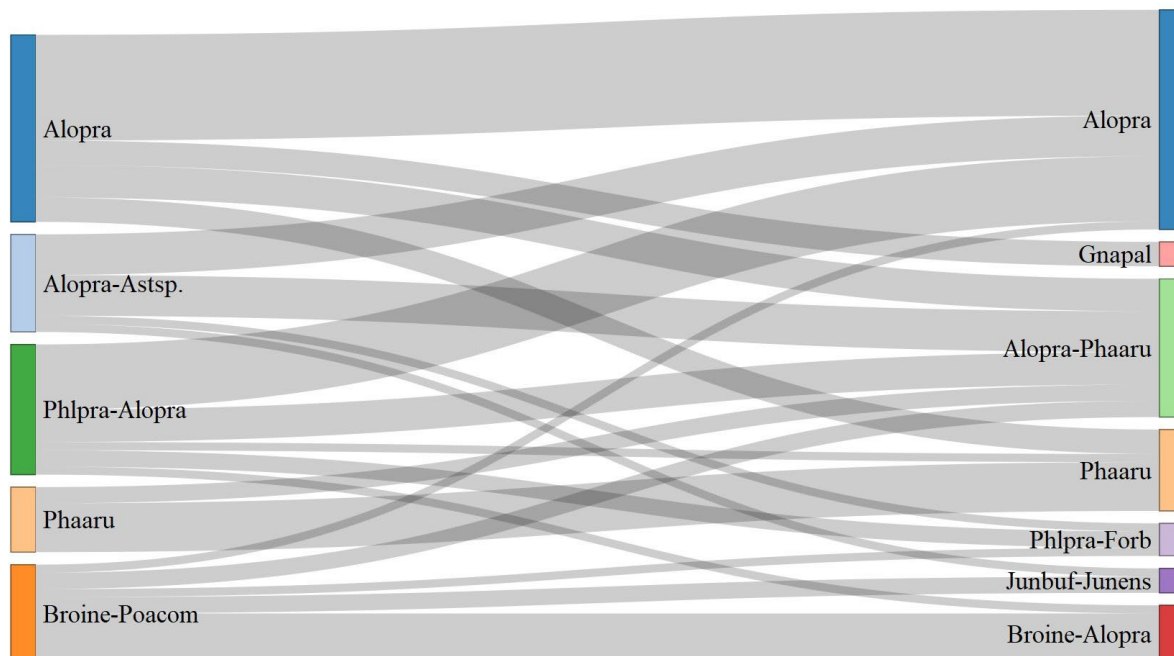


Figure 13: Flow diagram showing the number of plots in each plant community identified in 2012 (left) and 2017 (right).

***Phalaris arundinacea* distribution**

Phalaris arundinacea (reed canary grass) is an invasive grass that has successfully established in many wetland habitats across the United States. The species was collected by the Lewis and Clark Expedition in Montana, so is known to be native to the U.S. However, a Eurasian ecotype also has been introduced and is the highly invasive population. The invasive ecotype outcompetes native species, an especially problematic situation at Weippe Prairie where *P. arundinacea* and *C. quamash* occupy similar wetland habitats. Competition between the two species was not assessed in this study, but the aggressive nature and monotypic stands formed by *P. arundinacea* lead us to believe that it is the superior competitor if strong stands of native species are not already established to preclude its establishment. *P. arundinacea* has recently expanded along the restored ditch area, and its further expansion is likely unless treated. NEPE staff have had success controlling *P. arundinacea* with Ecomazapyr 2SL, and persistent treatment over the next few years should give the planted and other native species a chance to dominate the newly filled ditch and surrounding prairie (Fig. 14).

Where it was recorded in 2012 (13 of 71 plots), *P. arundinacea*'s cover ranged from 1 to 95% and averaged 47%. Although recorded in more plots (20 of 71 plots) in 2017 than 2012, *P. arundinacea* cover ranged from 1 to 70% and averaged 27%. Despite differences, the average cover across all plots did not differ between years (avg in 2012= 9%, se = 2.9%; avg in 2017 = 8%, se = 2.0%).

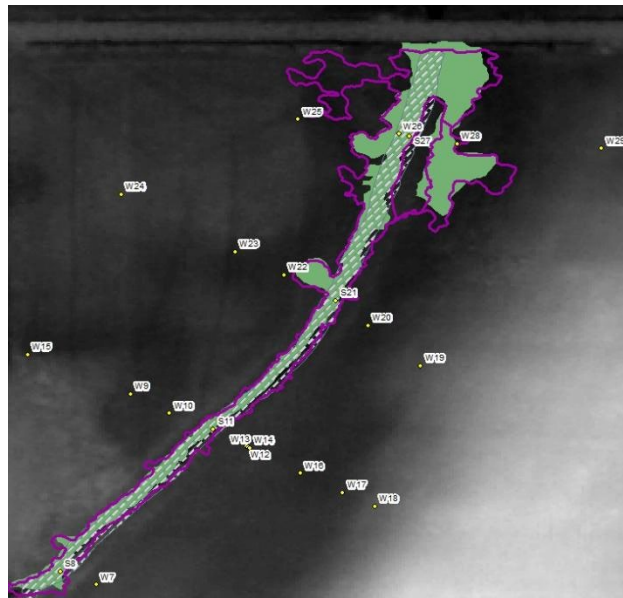


Figure 14. Area occupied by *Phalaris arundinacea* in 2015 (green shaded area) and 2017 (within purple line, but mostly outside of gray stippled area that is the infilled ditch). *P. arundinacea* expanded in the upper portions of the image, which is just south of the culvert under Larson Road.

SOILS

Soil density relationships to camas

The hardpan is a dense and hydraulically restrictive subsoil located 30 to 80 cm below the ground surface (Fig. 15). We found no relationship between hardpan depth and camas density when

considering all 166 sample locations ($R^2 = 0.02$; Fig. 16). However, analyzing trends within each transect reduced the noise introduced from comparing different areas of the prairie. The average within-transect relationship between camas density and hardpan depth revealed a negative relationship, but still with much scatter (mean $R^2 = 0.11$, $n = 7$ transects). We believe that the high scatter within the relationships is not strong enough to guide management practices.

For the three transects where we assigned camas a low to high value density of 1 to 4, a one-way ANOVA revealed a significant difference in depth to hardpan among the four density classes ($F = 3.38$, $p = 0.03$). The lowest camas density locations (class 1) had significantly deeper hardpan than did classes 2 and 4. Thus camas was found in low densities in areas where the hardpan was deeper than 70 cm below ground. Where the hardpan is within 70 cm of the ground surface sites may be capable of supporting relatively dense camas, but these areas today support both high and low densities. Thus, the density analysis identified where camas does not grow in relation to hardpan, but it does not specify that camas will be found in areas of near-surface hardpan. In creating expectations for restoring high density camas at Weippe Prairie, areas with a hardpan within 70 cm of the ground surface may have the highest restoration potential.

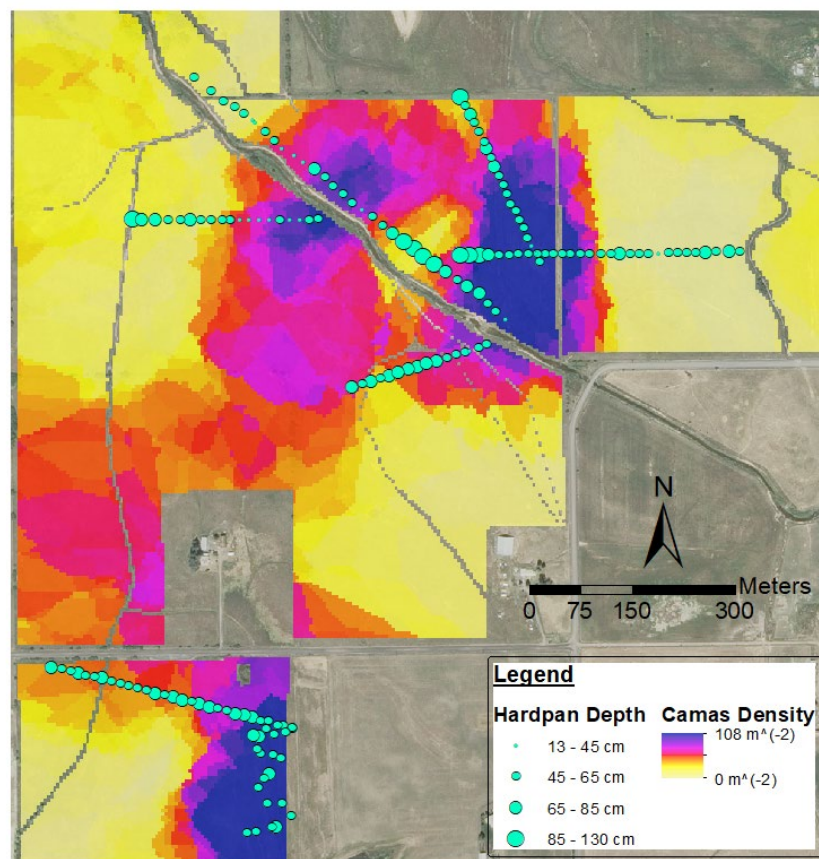


Figure 15. All points surveyed in the hardpan survey. Points are sized according to the depth of hardpan, and background color corresponds to 2011 camas density from the NEPE annual survey.

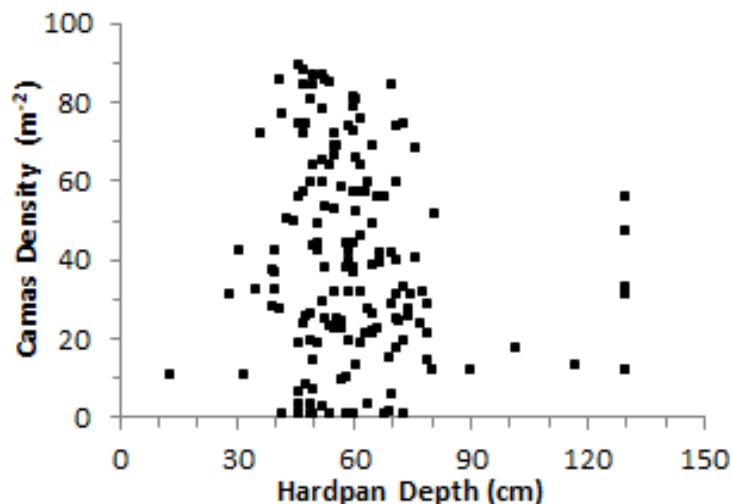


Figure 16. Camas density as a function of hardpan depth at Weippe Prairie (n = 166).

Soil compaction from vehicle traffic during restoration

The infilled, compacted, and reference soils of Weippe Prairie had different soil density profiles after ditch filling, but they were nearly identical two years after construction (Fig. 17). For measurements taken immediately after construction, heavy machinery had compacted the pre-existing prairie and caused it to have the highest density in the upper 20 cm of soil. In contrast, the fill zone resembled the reference prairie to a depth of 30 cm, below which soil was more compacted. This unnaturally high soil density zone was below the primary rooting depth, and was an intentional effort to suppress buried reed canary grass from re-emergence after burial. The fill zone's upper 30-cm, the primary plant rooting zone, achieved the targeted density profile to facilitate plant establishment.

The soil survey completed in 2017, two years after the ditch filling, indicated important changes to the soil density profiles. The effects of heavy machinery compaction were no longer present, as the compacted prairie zone returned to a density that matched the reference prairie. This recovery occurred after freezing, thawing, and saturation during 2016 and 2017. After two years, the formerly compacted zone at Weippe Prairie should be loose enough to enable successful native seedling plantings and facilitate expansion of neighboring vegetation.

The second notable change that occurred after two years is that in the fill zone, soil density decreased 25-45 cm below ground. It is possible that buried *P. arundinacea* began to emerge, loosening the soil. The intentionally highly compacted soil evolved to a more natural soil density after two years.

Two years after ditch filling the soil density profiles across the three zones were similar. This suggests that the heavy machinery did not have a long-term effect on soil structure. It also means that the degree of soil packing done during filling will likely achieve the desired long-term soil density profile within 45 cm of ground surface.

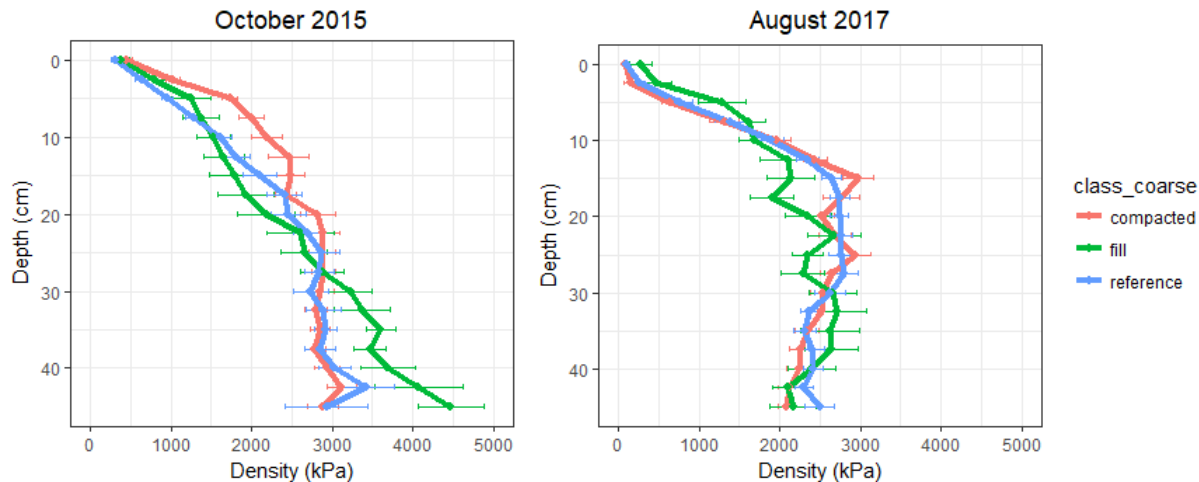


Figure 17. Soil density by depth in the filled, compacted, and reference zones immediately after ditch filling (left) and two years later (right). Lines are mean and standard error for the filled ditch zone (“fill”, green), the heavy machinery driving zone (“compacted”, red), and the surrounding reference prairie that was unaffected by construction (“reference”, blue). Note that 1) the initial near-surface compaction returned to reference conditions after two years, 2) the deep fill zone started uniquely dense but loosened over time, and 3) by 2017 the three zones had nearly identical density profiles.

DISCUSSION AND RECOMMENDATIONS

Measured water levels and redox potentials clearly indicate that both the reference and ditched areas (pre- and post-filling) at Weippe Prairie have wetland hydrologic regimes capable of supporting a diverse wetland community. However, due to land use changes including the creation of drainage ditches, the duration of saturation has been significantly reduced in areas. Ditch restoration by filling with mineral soil increased surface water retention, soil saturation, and plant-available soil water during the growing season. In this setting with very fine-grained soils and a hardpan, the wetland is wetted from above by local/regional precipitation including snowmelt water and rain, and diffuse sheet flow. This contrasts with most wetlands in the western U.S that are supported by a water table connected to larger groundwater systems. At Weippe Prairie, retention of local surface inputs naturally occurs because of low gradient topography, diffuse sheet flow, and ponding. Removing a constructed ditch reduced drainage and increased the duration of ponding, conditions required for hydrologic restoration of Weippe Prairie.

Prior land uses of Weippe Prairie included grazing, hay production, and ponderosa pine cultivation. Hay production is very common across the West in areas wetted by precipitation or irrigation systems. Hayfield creation typically included plowing the land and introducing Eurasian pasture grasses, including meadow foxtail, timothy, red top, smooth brome, Kentucky bluegrass, compressed bluegrass, and reed canary grass. These species dominate Weippe Prairie today, where even after hydrologic restoration the plant community more closely resembles a meadow native to Bavaria than Idaho.

Camas density in the vegetation plots was nearly identical between 2012 and 2017. Both McDaniel and Falen (2011, 2014) and our team found no relationship between water levels and camas density. They speculated that differences in camas density at the Prairie may be due to factors such as disturbance and past management rather than edaphic factors. Restoring the hydrologic regime will improve habitat for native wetland plants, but outcompeting the tall exotic pasture grasses will take a long and persistent effort. Considering the immense scale of vegetation conversion across the West, it is highly valuable that NEPE staff is working on methods to re-establish these native ecosystems. Refinement of techniques developed at Weippe Prairie could translate to widespread habitat restoration.

Because exotic pasture grasses dominate Weippe Prairie, efforts to control exotic plants, particularly reed canary grass, and planting of native nursery grown plants is likely necessary to restore vegetation to more closely resemble a native Idaho wet meadow. The species planted in the ditch restoration have established and grown, and a larger scale efforts at Weippe could result in vegetation changes that benefit the function and appearance of the entire prairie site. We suggest additional plantings of *Carex pellita*, *Scirpus microcarpus* and other native clonal plants for long-term vegetation restoration. Camas propagation research that NEPE is pursuing could provide useful information for its restoration. However, camas plants are found in areas dominated by exotic grasses, and it appears that divergent growth forms and seasonality of camas growth do not allow it to directly outcompete exotic grasses.

Future restoration projects at Weippe Prairie should target both small and large ditches. Because of the importance of the prairie's near-surface hydrology, even very small channels can dewater areas and have large hydrologic impacts. Restoring Weippe Prairie would mean filling additional channels, and where possible, reconnecting the areas south and north of the road, which presently has only limited culverts. Culverts require that shallow groundwater and sheet flow be channeled into single streams to be moved beneath a road. However, after concentrating into a channel it is difficult to spread out the water again to wet the broader prairie. To minimize concentration of flow into road culverts, we have installed permeable base roads at other NPS units. This design could be considered for roads that cross wetlands at Weippe Prairie to further improve hydrologic connectivity, thereby improving ecosystem function and creating a more authentic visitor experience.

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APPENDIX A. PHOTOS OF THE STUDY AND METHODS



Figure A1. A monitoring well in a reference area that is surrounded by *Camassia quamash*.



Figure A2. A station that was used to measure the oxidation-reduction potential of the near-surface soil during the growing seasons of 2012 and 2013.



Figure A3. In the foreground a plywood dam causes overbank flows from the ditch that was subsequently permanently filled. In background is the redox station located near Well 12.



Figure A4: Excavation of ditch and removal of *Phalaris arundinacea*. Standing around are Derek Schook and David Cooper.



Figure A5: The ditch being excavated, where undercut banks were exposed and *Phalaris arundinacea* was mechanically removed before infilling occurred.



Figure A6. Infilling the ditch. The foreground shows the already filled and compacted ditch, and the weed-free topsoil at center was used for planting.



Figure A7. Measuring soil density profiles along a transect in the filled zone. Surveyors shown are Derek Schook and Katy Matthews.



Figure A8. Vegetation survey conducted around a well (left) and along a transect (right) in July, 2017 . Surveyors shown include Andrea Borkenhagen, Devin Stucki, Derek Schook, Katy Matthews, and Heidi Becker.



Figure A9. Line intercept transect along ditch (white tape) and perpendicular transect across ditch fill area (yellow tape).



Figure A10. Planted and spontaneously germinating vegetation within the filled ditch zone. Native sedges are seen in foreground, and *Phalaris arundinacea* is at left.

APPENDIX B. SUPPLEMENTARY FIGURES

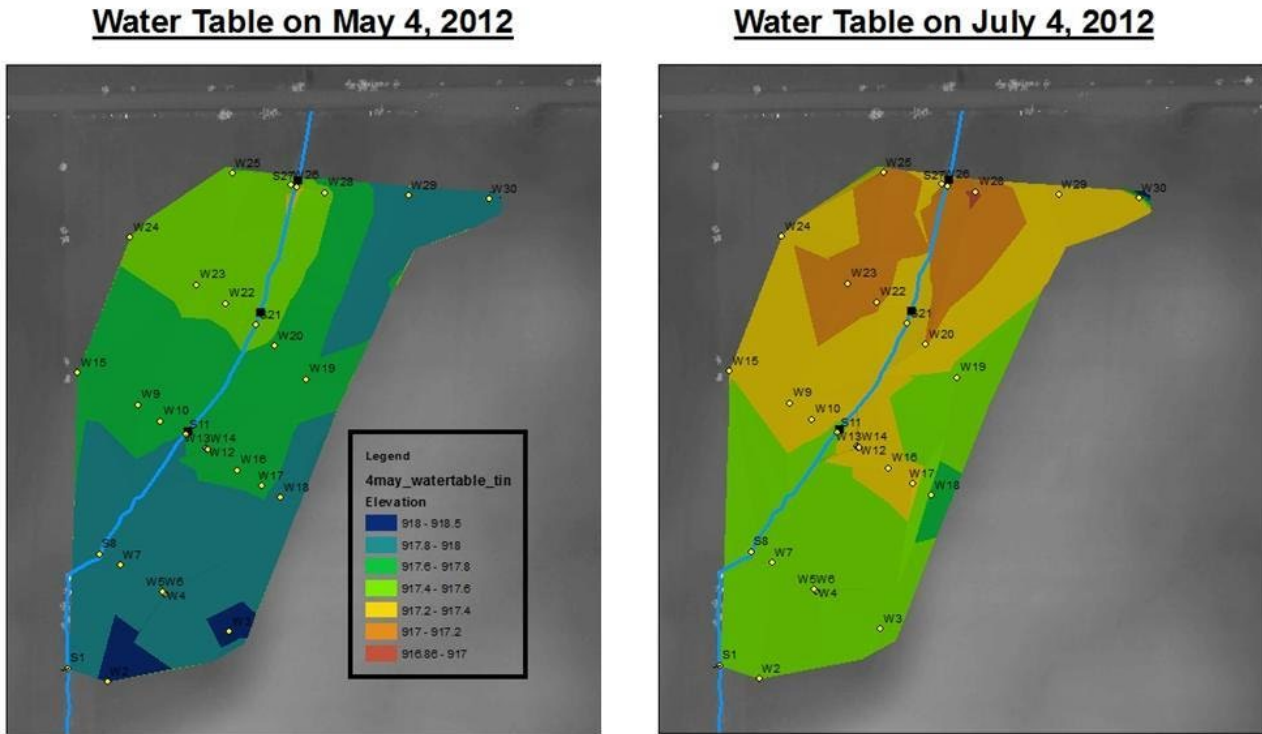


Figure B1. Water level elevation during an early season wet period (May 4) and dry (July 4) late season period in 2012. Generally, on both dates water levels declined to the north and toward the ditch, showing that groundwater exits the prairie through the ditch outlet. The relatively constant water levels perpendicular to the ditch indicate that increasing water level in the ditch will markedly affect water levels throughout the area. Interpolation method is triangulated irregular network. Contour interval 20 cm.

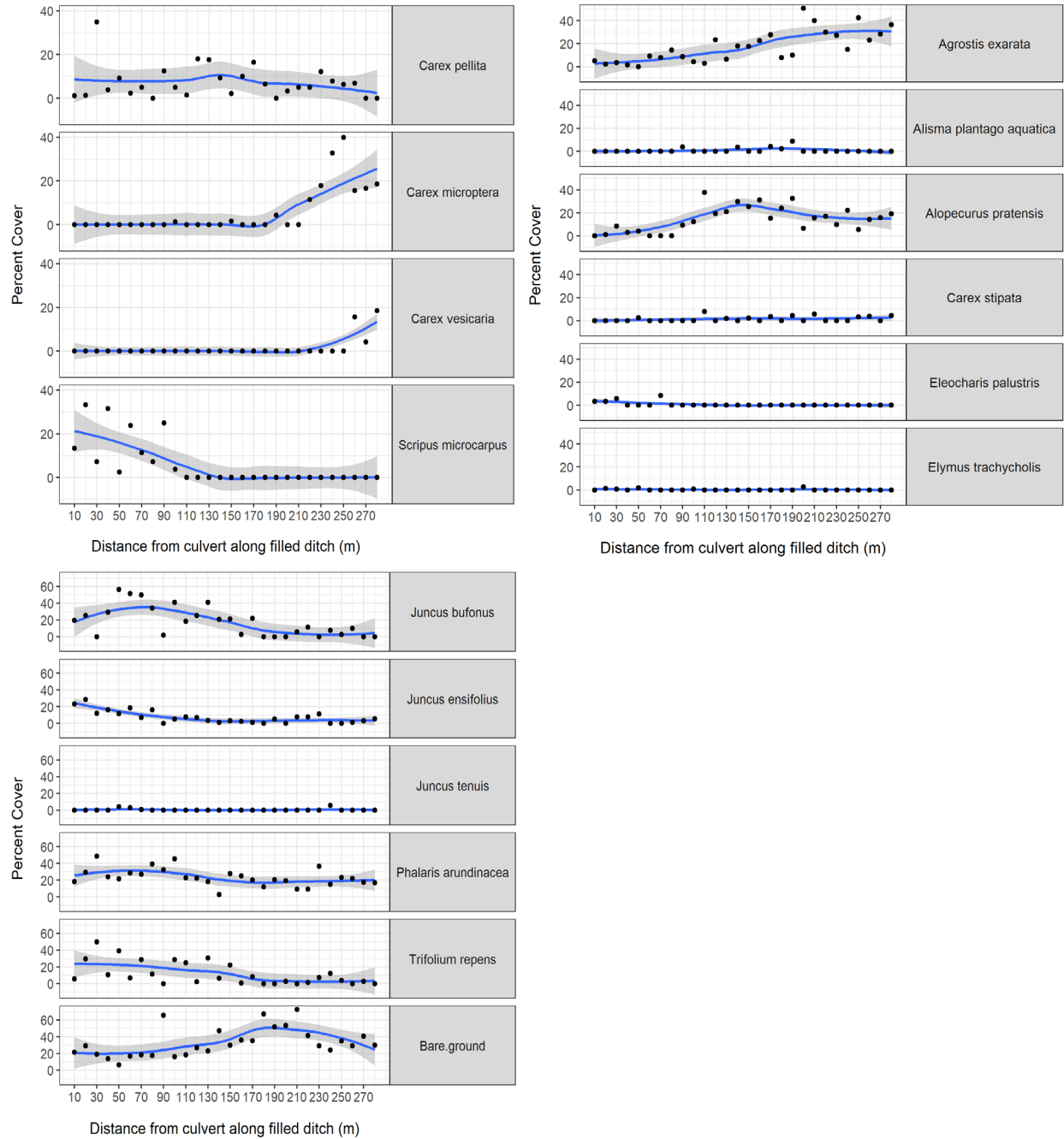


Figure B2. Absolute percent cover of planted and opportunistic species and bare ground along the ditch-fill transect. Line with standard error in gray represents the nonparametric local regression. Transect starts at the culvert (0 m) and runs to the southern end (280 m). Cross transects were surveyed every 10 m from edge of the disturbed area across the ditch-fill.

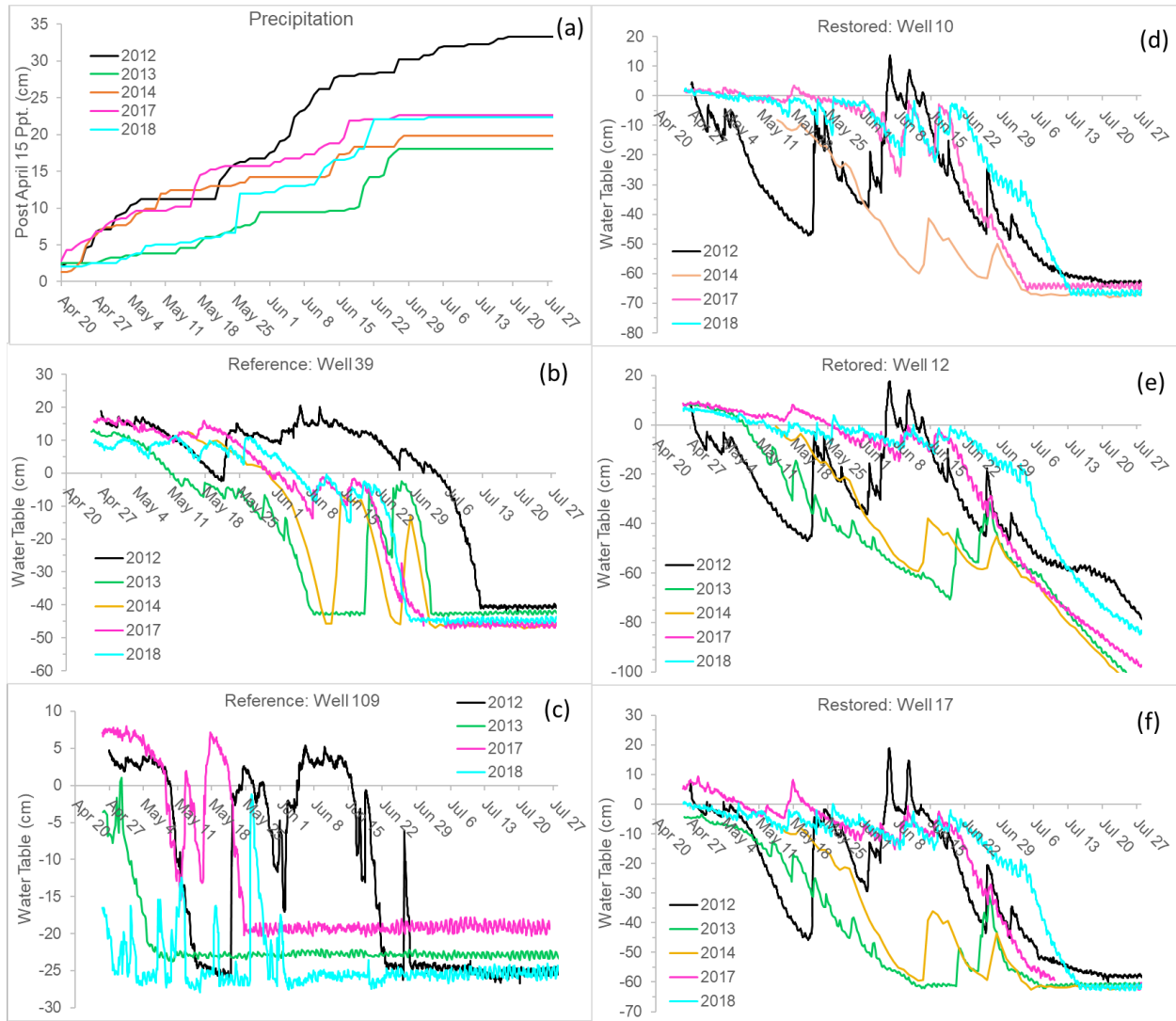


Figure B3. Figure 4 with additional data presented from Wells 10, 13, and 109. Reference wells on the left side (b,c) show the pre-restoration year 2012 to have been the wettest summer because of high rain (a), but in the restored area wells at right (d, e, f) years following restoration had the highest water levels.