TITLE: The ecological benefits of irrigated agriculture and potential risks under changing water allocation/supply

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LOCATION: Larimer and Weld County, CO

## **INTRODUCTION**: Wetland and riparian ecosystems in the irrigated landscape

Human influence on ecosystems and natural processes are nearly universal in populated areas. In areas where agriculture is a dominant land use the direct influence on plant and animal communities can be severe. Where agriculture is limited by low precipitation, irrigation has been developed as a tool to grow crops. Irrigation water diverted from rivers and streams may cause several changes to the regional environment. First, as water is removed from natural streams the water quality, fish habitat, and riparian vegetation are often degraded as the hydrologic context in which these communities developed is altered. As water is moved out of the rivers and streams it no longer interacts with its historic floodplain and is delivered to uplands for agricultural use. Another effect of irrigated agriculture is the creation of novel habitats along diversion ditches and canals. The physical characteristics including width, depth, length, construction material and position on the landscape interact with the flow properties to influence the type of riparian communities that develop along them. These man-made ecosystems may be viewed as a positive outcome.

Riparian ecosystems are disproportionately productive relative to the surrounding landscapes in most areas of the world (Naiman et al. 1993). They function to store, transform and cycle nutrients, organic matter (Tank et al 2010) and sediment (Steiger et al. 2003), and link terrestrial and aquatic ecosystems at local and landscape scales (Fisher et al 1998, Harvey and Gooseff 2015). Agriculture in arid and semi-arid regions requires water for irrigation, and streams provide this water in many areas.  Surface water is diverted from streams, and transported in constructed ditches to croplands. Riparian vegetation develops along the irrigation ditches. The seasonal flows, physical characteristics of the ditch banks, and vegetation management by ditch companies and adjacent landowners influence the composition of the plant communities.

*Prevalence on the landscape*

In semi-arid agricultural landscapes, irrigation ditches can be more numerous than streams and rivers, with the channel length equaling or exceeding stream length. The majority of our study area is District 3 of the South Platte Irrigation Division, east of the Rocky Mountain front. More than 110 structures divert water from the Cache la Poudre River which receives water from trans-additions from the Colorado River Basin and Laramie River Basin. More than 36 of these structures divert water into 1,073 kilometers of irrigation ditches. This is nearly equal to the mapped length of streams in the same area of 1,147 km, including perennial, intermittent and ephemeral streams. It should be recognized that the ditches are not replacing stream features, but are additional channel features on the landscape.

These channels are generally constructed of earth, with concrete sections used to limit seepage. These channels have aquatic habitat of varying quality related to the patterns of flow, maintenance activities and bed substrate. The physical characteristics of the ditches varies as some are more than 100 km long, 18 meters wide and 2 meters deep. Others were only a few kilometers long, less than 1 m wide and 0.5 m deep. Streams had similar physical variance from small first order streams to the Cache la Poudre River that is more than 20 m wide.

Tailwater wetlands are an example of indirect wetland ecosystems that can be created by leaking irrigation ditches, as well as regionally higher water tables as a result of widespread irrigation. Within the District 3 portion of the study area, 1,433 hectares of emergent and woody wetlands were within 50 m of irrigated agriculture. These vary from seasonally wet depressions dominated by sedges (*Carex* spp.) and grasses to more permanently saturated wetlands dominated by cattails (*Typha*). An additional 3,542 ha of ponds and lakes were within 50 m of irrigated fields. Combined, these account for 10.5% of the landscape.

These ecosystems occupy a relatively small spatial footprint on the landscape but through ecosystem functions they could play a significant role in regional biodiversity and nutrient cycles in the agricultural landscape. Changes in the extent or type of irrigation could dramatically impact the location, type and quality of these ecosystems. We investigate the directly created riparian and aquatic ecosystems as well as tailwater wetlands dependent on irrigated agriculture and how their location and condition could change under future climate and water use scenarios.

## STUDY PURPOSE

### *Comparing Ditch Riparian Ecosystems to Stream Riparian Ecosystems*

Riparian ecosystems in many parts of the western U.S. have been degraded and their extent reduced through conversion of floodplains to agricultural lands, altered flows due to dams and diversions, and the introduction of non-native plant species. While natural streams and rivers have seen a decline in riparian extent and quality, the formation of riparian vegetation along manmade channels could offset some of this loss. In addition to the impacts to the riparian ecosystem, the aquatic ecosystem of the rivers and streams has also been impacted by human activities. The flow regime of irrigation ditches could mimic the historic intermittent flow regime of many streams in the region. Aquatic macro-invertebrate communities are commonly used as a surrogate for many aquatic ecosystem attributes including water quality, sediment, and food resources.

Objective: Assess the riparian vegetation and aquatic macro-invertebrate communities of irrigation ditches and streams, and make comparisons between the two groups.

*Nitrate Transformation and Uptake in Agricultural Wetlands*

Wetlands that have formed from runoff from irrigation water from agricultural fields through surface and subsurface flow have the potential to intercept non-point source pollutants. Best management practices including, improved fertilizer and irrigation efficiency, conservation tillage practices, and crop rotations have helped to reduce the amount and mobility of contaminants in surface and groundwater. However, in many portions of Weld County nitrate is a regional groundwater pollutant and decades of BMP's have not made significant improvement to the groundwater chemistry. Nitrogen, as nitrate and ammonium, is a large component of commercial and manure based fertilizers. Nitrate can become a pollutant with adverse environmental and human health affects at concentrations exceeding 10ppm (EPA 2012). Nitrate is a soluble ion that travels easily through surface and subsurface water, as it does not bind well to soil particles. It is however, readily taken up by plants and used by micro-organisms to complete respiration in the absence of oxygen by denitrification.

Natural ecological functions of wetlands including microbial denitrification and plant uptake of nutrients can trap and/or transform nitrate. Wetlands have often been measured to be more productive, in terms of biomass, than surrounding ecosystems, thus they may have a larger need for nitrate as a macro-nutrient. Wetlands are also positioned in the landscape such that they concentrate surface and subsurface water creating anaerobic soils for at least part of the year. These two characteristics combine to create conditions favorable to trap or transform nitrate into other benign nitrogen containing compounds.

Objective: Examine the biotic and abiotic characteristics of wetlands including: water table dynamics, microbial activity, plant community structure, biomass and chemical composition, soil organic matter, and groundwater nitrate levels to determine the efficacy of these processes.

*Change in Irrigation, Risk to Irrigation Dependent Ecosystems*

Ditch riparian vegetation and agricultural wetlands are unintended consequences of irrigated agriculture. Two benefits studied here are habitat for plants and animals and nutrient cycling for pollution mitigation. These ecosystems are completely, yet indirectly, dependent on irrigation. If irrigation schedules, efficiencies and extent changes, these ecosystems and their beneficial attributes and processes could also change.

The study region is the northern end of the Colorado Front Range which is experiencing a surge in population growth without a comparable increase in water supply. Irrigated agriculture has been targeted as a source of water for growing municipalities. Moving water from agriculture to cities and towns could take several forms including temporary leases, semi-permanent transfers and permanent water rights buyouts. In any of these situations, less water will be flowing in irrigation ditches. This could affect the riparian vegetation through die off of woody plants and altering species abundance. Aquatic ecosystems might see more direct and immediate changes as low and zero flow periods dramatically affect the dissolved oxygen and temperature of water, affecting the aquatic macro-invertebrate communities. We use the riparian vegetation and aquatic ecosystem attributes from the first part of this study and prepare a risk analysis map of ditch reaches where flow could be reduced to identify locations of likely habitat change. Wetland nutrient processes are likely to be more site specific for a paired wetland an agricultural field. This investigation does not go to that level detail across the study region.

Objective: To determine the location and severity of reduced flow in irrigation ditches that could impact ditch riparian ecosystems.

## METHODS

*Study Area*

The study area in north-central Colorado is representative of semi-arid regions in the western U.S. with extensive irrigated agriculture. Precipitation averages 250 millimeters during the summer and 135 mm during winter (www.usclimatedata.com). Total annual precipitation is insufficient to support the desired regional crops; corn, beans and vegetables. For example, most corn varieties require in excess of 500 mm of water during the summer in eastern Colorado (Schneekloth and Andales 2009). Water for irrigation is diverted from rivers fed by melting snow in the Rocky Mountains, stored in reservoirs and applied to crops from late April through September. The study area is divided into a West region dominated by higher density of residential land use and an East region of predominately agricultural land use.

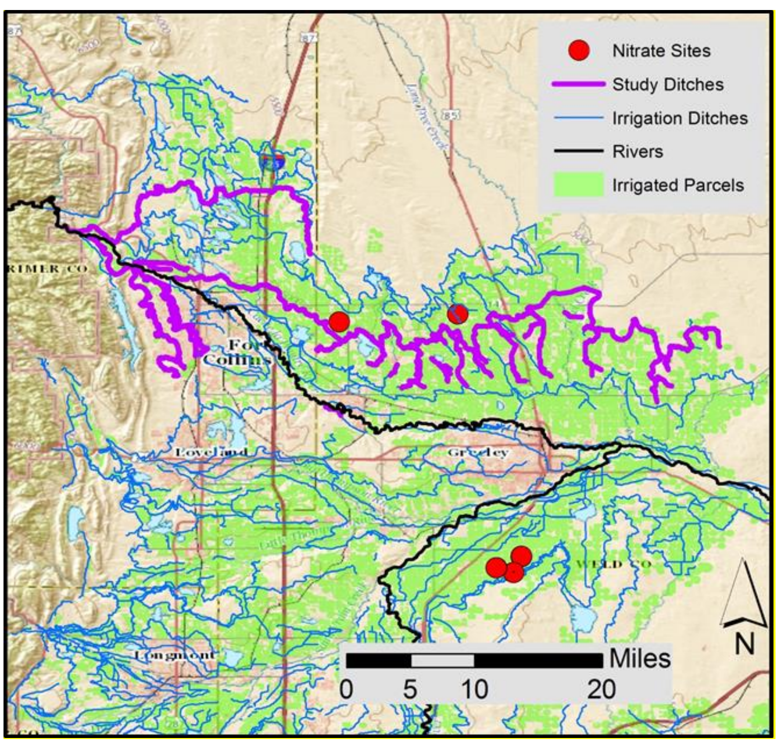



Figure 1. Map of the study area, showing irrigations nitrate study sites (red dots), the Cache la Poudre River flowing west to east and the South Platter River, flowing north then east (both black lines), the irrigation ditch network (blue lines), the sampled irrigation ditches (purple lines) and the extent of irrigated parcels in 2005 (light green area).

This study occurred on ditches managed by four irrigation companies that had a combined 326 kilometers of channels that provided water to 40,118 hectares of irrigated crops. Channel width and depth varied from laterals that were 1 m wide and 0.6 m deep, to main canals that were up to 18 m wide and 2.5 meters deep. The Cache la Poudre River is the main water source for the study areas and was sampled at three locations as a large stream. Small streams included Spring Creek in the West region, and Lone Tree Creek, Owl Creek and Willow Creek in the East region. Stream sites do not represent pre-settlement conditions because human impacts have resulted in a variety of impacts including partial dewatering, invasive plant species are present, and wastewater flows down these streams.

## *Irrigation Ditch Methods*

### *Flow Characteristics*

Average daily flow data were available for ditches at the diversion structure (Colorado Decision Support System, http://cdss.state.co.us/ONLINETOOLS/Pages/StructuresDiversions.a spx). Stream flow data for the Cache la Poudre River was available from U.S. Geological Survey gages at Fort Collins (06752260) and Greeley (06752500). Daily stream flow data is not available for Lone Tree Creek during the study period April 1 to September 30 but was included and Owl Creek and Willow Creek are ungauged drainages. Four ditch diversions were gauge including Larimer #2, New Mercer, Larimer and Weld, and Pleasant Valley and Lake.

Nine metrics were calculated from the daily stream flow describing the variability, timing, and duration of flow. Zero flow days were recorded after the ditch or stream began to flow during the study period.

### *Riparian Vegetation*

At each site three transects perpendicular to the channel were spaced 5 bankfull channel widths apart. Three geomorphic surfaces were sampled (Figure A); (1) bank surface adjacent to the channel extending up to (2) the flat top/floodplain surface and, (3) side/terrace surface that extends into the upland or the backside of the earthen berm used to construct the ditch. These are not always present for ditches or streams in flat terrain. Only geomorphic surfaces present were sampled. Plant cover was visually estimated for five 1 $m^2$ plots on each geomorphic surface on each side of the channel for each transect. Cover was recorded for each vascular plant species using a modified Braun-Blanquet classification (trace, <1, 1-2, 2-5, 5-10, 10-25, 25-50, 50-75, 75-95, >95%). Vertical structure was categorized for each species using height classes (<1 m, 1-2 m, 2-5 m, 5-10 m, >10 m).

Plant guilds were developed using the concepts of Merritt and Bateman (2012), and included: wildlife food type, (Culver and Lemly 2013), coefficient of conservatism (Rocchio et al 2007), wetland indicator status (Lichvar et al 2012), growth habit, duration and nativeness (NRCS 2015). Ecological groups were created using the kR means grouping procedure in Primer, with a maximum of 10 groups. Species were replaced by the guild they belonged to and the cover combined.

Descriptors of site characteristics were used to separate groups of channels at three spatial scales. The coarsest scale characterizing the channel origin: stream or ditch. The middle scale identified the region: East and West. The finest spatial scale identified the dominant cover type: Dense Canopy, Light Canopy, Shrub, Herbaceous, Concrete. These three scales could be combined into a three level descriptor such as Ditch-West-Shrub. A variety of comparisons were made using these spatial scales.

*Aquatic Macro-invertebrates*

Aquatic macro-invertebrates were sampled in the channel section of each transect using a 500-micron D-ring kick net. The top 5 cm of sediment and submerged vegetation were disturbed for 3 minutes. A sweeping motion under the water was used to simulate flow in stagnant pools. Micro-habitats including riffles, pools, banks, submerged and aquatic vegetation were collected in one sample. Water temperature was measured during each sample in 2015 and presence of algae, submerged vegetation, and periphyton were recorded during all collections.

All insects were picked from samples and preserved in 80% ethanol. Volume based subsampling was used in limited cases where insects exceeded several hundred individuals. Individuals were identified to genus for most groups; worms and leaches to family. Physical and ecological traits (Poff et al. 2006) of genera and families were incorporated to group taxa into guilds with similar habitat and food preferences following the same statistical methods as for plant guilds.

## *Tail-water Wetland N-functioning Methods*

Soil Characteristics: Physical soil analyses (bulk density, organic matter content, moisture content) were performed on two horizons, encompassing the top 2 feet of soil. The percent of organic matter was measured using the loss on ignition method (Nelson and Sommer 1982). Soils were dried at $55^0$C then crushed and 4 g samples were burned at $550^0$C. Bulk density was samples were collected using a brass ring with dimensions of 6 cm diameter and 4 cm height. Care was taken to not compact the sampled soils. These were dried to a constant weight at $55^0$C. Bulk density was calculated using a known volume of soil and dry weight.

Aboveground Biomass: Above-ground plant parts were collected from 100 $cm^2$ subplots within the vegetation plots for biomass and analysis of tissue chemistry. These collections were made in mid-august to maximize plant height and made within 5 days to limit additional growth between sites. Samples were dried in a $55^0$C oven until a constant weight was recorded (~2 weeks).

Microbial Biomass: Soil samples of at least 100 grams were collected from the top two soil horizons, excluding the O-horizon. These were weighed and dried in a $55^0$C oven for 5 days to determine dry weight. A control and experimental beaker were set up with 10g of field wet soil in each. Chloroform (5ml) was added to the experimental beaker and both were capped and allowed to incubate for 24 hours. After venting for 2 hours to remove the chloroform, 50 ml of 0.5M $K_2SO_4$ was added to the beakers and shaken on a table for 90 minutes. The contents were poured through Whatman #1 filter paper and the subsequent liquid was diluted to 1/10 concentration to reduce the concentration of potassium salts which could damage the machine which measures the concentrations. Concentrations were converted into standard units of µg C/ gram dry soil.

Hydrology: Groundwater wells were installed using a hand-auger. Drillers sand was added to surround the 2.5" diameter, diagonally slotted PVC pipe and a bentonite clay cap used at the ground surface. Slots ended just below the surface. Wells were placed in at the boundary of the field and wetland, just inside the wetland area to limit risk of damage by farm machinery. Additional wells were placed at 10m intervals into the wetland with a minimum of 2 and maximum of 4 at each site. Replicate wells were installed along a parallel transect, 10 m away. Only 1 transect was instrumented with water level loggers, measuring every 30 minutes from the growing season (April-October). Shallow groundwater at each sampling location was categorized into two groups as the percentage of the April-Sept growing season where water present within 12" of the soil, roughly the boundary between the A and B horizon and within 24" of the soil representing the most active denitrification zone.

Groundwater Chemistry: Groundwater samples were collected every 2-3 weeks for a total of 7 possible samples per well. These were analyzed for nitrate levels by the Colorado Water Quality Division lab in Denver after being hand delivered on the same day. Samples were extracted after flushing the well volume twice. Samples were pre-filtered with a 0.02 micron PFE filter with 20ml of water pushed through a syringe. Deionized water was used to clean the instruments between each sample. Water pH, electro-conductivity and temperature were tested using a multi-probe meter (Thermo Scientific Orion meter) during August.

In-Situ denitrification experiment: In-situ denitrification measurements were made in tailwater wetlands. The method is similar to intact core incubations in the laboratory, however the chambers utilized in this study were installed in the wetland and not removed during the measurement period. This method was selected to measure the realized denitrification under field conditions compared to potential denitrification under laboratory conditions (Groffman et al 2011). Incubation chambers were constructed of 4" PVC tubes, 30" in length. The caps were drilled and fitted with a brass port, silicone tubing and stopper for gas sampling. The chambers were pounded into the ground, minimizing and measuring compaction. Caps were installed and sealed with silicone caulk and petroleum jelly for an airtight seal (Figure 2). Acetylene was added at a concentration of 10% of the headspace volume. This varied by chamber depending on the compaction. Following a 12-15 hour incubation period, 30ml samples were withdrawn from the headspace using s sterile syringe and injected into an evacuated 20ml glass scintillation vial with butyl septa. The additional 10ml were forced into the vial to ensure each sample could be run twice if necessary. Samples were taken at 1-2 hour intervals after the initial incubation period. Extremely saturated soils were allowed to incubate for 18 hours before sampling. Samples were processed on a Shimadzu GC14B gas chromatograph with FID, methanizer ECD, and autosampler for acetylene ($C_2H_2$), nitrous oxide ($NO_2$), carbon dioxide ($CO_2$) and methane ($CH_4$).

Figure 2: Equipment to test microbial denitrification, two installed incubation chambers located lower enter.

*Scenario Methods*

The transfer of water rights can do not need to be adjacent to proposed future proposed municipal uses to be Information on proposed residential development is not widely available. Thus to estimate the potential for flow reductions, I used a spatially random sample of townships that covered the study area

Townships that intersected the ditch services areas were sampled randomly for inclusion in the change of use scenarios. In each replicate, if a township was selected, all ditch segments in the township were assumed to have a 5% reduction in flow. For mainstem ditches, downstream townships also reduced flow by 5%. Thus a mainstem ditch segment with 4 townships selected downstream would be recorded as having 20% reduction in flow. The was repeated 5 times and the average reduction in flow recorded for each segment.

Habitat quality index was generated from riparian vegetation metrics for the bank surfaces only. These were expected to be most responsive to changes in flow. The number of woody strata present (STRATA), percent cover of species identified as obligate and facultative wetland plants (WET), the % cover of species with C-values greater than 4 (C_VAL), and the percent cover of native species were combined into the habitat score (NATIVE). Values were normalized for

STRATA and C_VAL to bring them into equal weight with the other two factors. A maximum possible score of 400 and a minimum of 0 was possible.

Pearson correlations were made between physical characteristics of the ditch network and the habitat score, including distance from diversion (DIST), bankfull channel width (WIDTH) and a scalar representing landuse (LAND). Landuse was categorized and converted into a scalar using Table 1.

Table 1. Landuse types and scalars.

| Landuse | Scalar |
|---|---|
| Natural areas | 1 |
| Pasture, Hay fields | 3 |
| Light Residential | 4 |
| Dense Residential | 5 |
| Agriculture (row crops and livestock) | 6 |

It is important to note that individual field and ditch management was not considered here and the universal reduction of flow by 5% to ditches within a township was a subjectively determined amount.

## RESULTS

### *Irrigation Ditch Results*

Hydrology: Streams flowed for more days during the April 1-Sept 30 period and had more day to day variability (skew) than ditches. Peak flow in 3 ditches occurred approximately 30 days later than streams with 1 ditch with a peak 30 days earlier. Lone Tree Creek recorded an average of 16 zero flow days per year which was comparable to the Pleasant Valley and Lake Canal. The Larimer #2 canal flow for 68% of the study period over the 17-year average compared to the Larimer and Weld, a large ditch providing water to the eastern region which was flowing for 93% of the study period.

Table 2. Selected hydrologic metrics. Flow value units are cubic feet per second (daily mean, daily median, daily max, daily min), Julian date begins on Jan 1 and counts consecutively.

| | Poudre @ Fort Collins | Poudre at Greeley | Lone Tree Creek | Larimer and Weld Canal | Pleasant Valley and Lake Canal | New Mercer | Larimer #2 |
|---|---|---|---|---|---|---|---|
| # years analyzed | 17 | 17 | 7 | 17 | 14 | 17 | 17 |
| daily skew | 2.19 | 3.22 | 5.63 | 1.03 | -0.56 | 0.99 | 2.03 |
| daily mean (cfs) | 293.52 | 237.76 | 11.36 | 150.82 | 26.63 | 13.97 | 16.83 |
| daily median (cfs) | 94.88 | 82.72 | 6.04 | 108.32 | 30.03 | 8.82 | 6.96 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| daily max (cfs) | 2289 | 1699 | 139 | 588 | 50 | 57 | 105 |
| daily min (cfs) | 4.9 | 19.9 | 1.1 | 0.9 | 0.5 | 0 | 0 |
| duration (days) | 183 | 183 | 163 | 170 | 168 | 146 | 125 |
| zero flow days | 0 | 0 | 16 | 9 | 14 | 37 | 58 |
| Julian date of max | 161 | 179 | 177 | 193 | 213 | 142 | 215 |

*Riparian Vegetation*

Plant cover was analyzed in 3,227 plots on bank and top/floodplain surfaces. Herbaceous plants accounted for 50% of total number of species, grasses 32% and shrubs and trees combined for 14% with 51% of all species identified as native. Woody sites in the East region had lower cover of native species with only 27%, than woody West sites with 60% native cover. Additional characteristics of communities are shown in Table 3. When present, *Phalaris arundinacea* and *Carex emoryi* dominated the bank surface (Figure 3).

Figure 3: Examples of sites where the banks are dominated by *Carex emoryi* (left) and *Phalaris arundinacea* (right).

Table 3: Vegetation characteristics of sites categorized by region and channel type. The percentage of the total cover that was native species, percentage of the total cover that was bare sediment, number of species per site (Richness), the percentage of total cover of species with a moderate to high C-value of 6-9. All values are derived from the combine bank and top/floodplain surfaces.

| Group | % Native Cover | % Bare Sediment | Richness per site | % Mod-High C-value |
|---|---|---|---|---|
| *West Stream* | 38.8 | 14.0 | 30.7 | 11.4 |
| *West Ditch* | 45.2 | 15.6 | 25.6 | 48.5 |
| *East Stream* | 38.5 | 9.7 | 24.8 | 34.5 |
| *East Ditch* | 37.4 | 28.5 | 21.2 | 34.4 |

A PERMANOVA analysis of sites using the full vegetation data of the bank and top/floodplain surfaces indicated that channel type had a significant effect on vegetation composition (F = 2.37, p = 0.01). Grouping sites by region and channel type showed that West ditches and West streams were significantly different (t = 1.38, p = 0.037) while the same comparison in the East region did not indicate significant differences. A difference between vegetation of West ditches and East ditches was also significant (t = 1.96, p = 0.001), while streams were not different between regions. Tests using the cover of plant guilds resulted in the same findings.

Wetland Indicator Status for observed species ranged from obligate wetland (OBL) to upland (UPL) species. OBL and facultative wetland (FACW) species were 69% of the cover while only 44% along ditches. Major differences were evident for each channel types between regions. West ditches had a lower proportion of OBL and FACW species (33%) compared to East ditches (56%). The reverse pattern was observed for streams, with 76% of cover composed of OBL and FACW species in the West with 62% for East streams.

Mean C-value of plant cover at the plot level, was lower for the East region and for ditches within each region compared to the streams (ES = 3.49, ED = 3.13, WS = 4.49, WD = 4.37). West ditches had the highest cover of rare species (3.1%), those observed at fewer than 3 sites in the study, with east ditches having the lowest cover at (0.09%).

*Aquatic Macro-invertebrates*

New taxa were collected during each sampling visit during the two primary sampling years 2014 and 2015. A total of 153 taxa were identified; 145 to genus and 7 to the family level. The most diverse order was Diptera with 68 taxa, Coleoptera (22) and Ephemeroptera (16). A large portion of the remaining 48 taxa collected were rare and collected only once during the 3 seasons of sampling. The family Chironomidae (49 observed genera) comprised 57% of collected individuals and were investigated separately to track if changes in functional traits within the family agreed with those of the full macroinvertebrate community (Rocha et al 2012).

The region and channel type groupings did not separate using and nMDS on the Bray-Curtis resemblance matrix (Figure 4). Macroinvertebrate communities of streams were similar between regions (t = 0.824, p = 1) whereas those of ditches were different between regions (t =

1.486, p = 0.007). Macro-invertebrate communities of ditches and streams were not different in the East (t = 0.884, p = 0.759, nor the West regions (t = 1.112, p = 0.189).

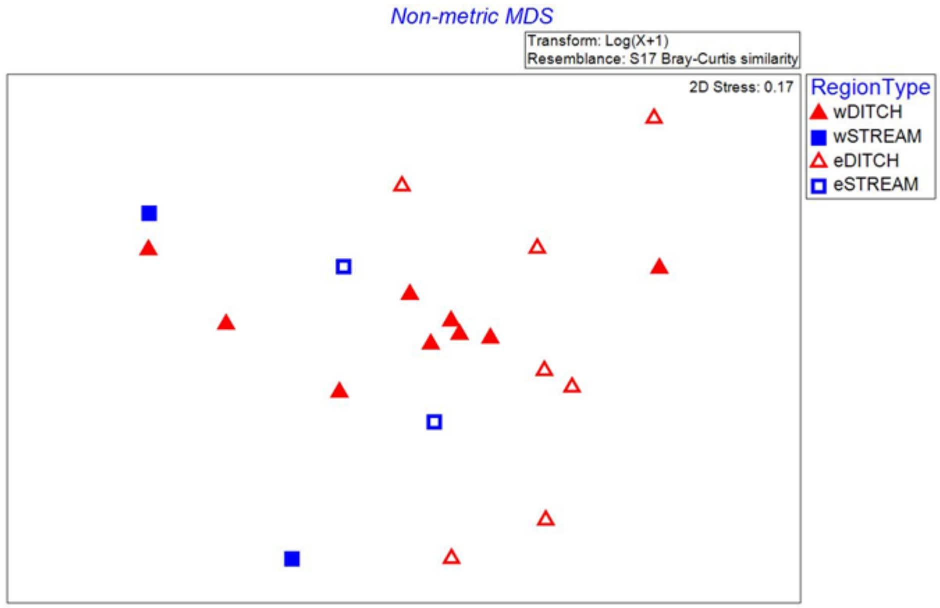



Figure 4: Non-metric multi-dimensional scaling plot of aquatic insect communities at 20 sites. Points represent pooled samples from 2014 and 2015. wDITCH = west ditch, wSTREAM = west stream, eDITCH = east ditch, eSTREAM = east stream.

Ninety-seven taxa were classified by functional trait data into ten groups by kR means classification (r = 0.941) This accounted for 86% of collected individuals. The differences observed with the full community at the genus level were not supported using the functional trait groups. Functional group H represented the most sensitive taxa, requiring cold water, clean water and were only present in significant numbers (>10% of total individuals in 1 west stream and 2 west canals). Six ditches in the study area had greater than 85% of individuals classified in the two most tolerant groups I and J dominated by Chiromomidae taxa. I did not find a difference in functional group composition between region and channel type groups. Substrate was found to have a significant effect on functional group composition in the West region but this could not be explored further due to a low number of replicates.

A distance based linear model (DistLM in Primer) on measured environmental variables including: distance from diversion, bankfull width, distance to upstream woody patch, length of upstream woody patch and water temperature in June, July and August was fair (0.44 with p = 0.001). A reduced list of 4 variables (June water temperature, July water temperature, bankfull width and distance to woody patch) were selected using AICc as the criteria. The same four variables were also selected using the BEST procedure in Primer with a Spearman rank correlation of 0.466.

### *Tail-water Wetland N-functioning Results*

Crop Type: The focus of the study was nitrate levels in wetlands adjacent to corn fields, however with a wet spring and late planting, the crops of several fields changed. Site E was planted with beans, S2 with wheat, and S1 was left fallow. B1 and B2 were planted with corn and F had a combination of corn and alfalfa.

Soil Characteristics: The northern sites, B1, B2 and F were characterized by a higher clay content (55%) and more organic matter (10.75%) than the southern sites S1, S2 and E with 22.5% clay and 5.5% organic matter. Bulk density in the north was lower (1.16 g/cm$^3$) corresponding to the higher clay content, in the south the sand increased the bulk density to 1.33 g/cm$^3$. The sample locations near the center of the wetlands in the northern sites had strong sulfur odor, indicative of anaerobic conditions. All three northern sites were adjacent to irrigation reservoirs and these wetland center sample sites were characteristic *Typha* marshes.

Aboveground Biomass: Above-ground biomass was highly variable depending on the dominant species. *Typha* were the most robust plants, followed by *Schenoplectus*, *Phalaris* and *Carex*. Each of these formed near monocultures at some sites. *Typha* measured up to 140" in height with a biomass of 15.5 kg/m$^2$ at site B1 and an average of 8.33 kg/m$^2$ across all sites. The biomass of the other dominant species was an order of magnitude smaller with *Schenoplectus* at 1.19, *Phalaris* at 1.55 and *Carex* at 0.82 kg/m$^2$.

Microbial Biomass: Microbial biomass varied dramatically between sites, within sites and even between soil horizons. I measured the microbial biomass for 13 of 17 sample locations. Typically, the upper horizon had higher values (5x on average) and sample locations further into the wetland had higher values (50% higher over 10 meters). The highest values were in the A horizon under *Typha* at locations with soils saturated about 50% of the April-Sept sampling period. Microbial biomass was consistently lower at two sites E and S2 with high EC levels in the water and obvious salt deposits.

Hydrology: Groundwater at the study sites appeared to be controlled by a combination of Irrigation, precipitation, and reservoir levels. Three sites were located on the edge of irrigation reservoirs between the crop field and open water. For two of these, the reservoir levels were fairly constant during the study period. A third would be dry through early June and be filled in the middle of the summer, raising the adjacent water table by several feet in less than a week. Rapid, but short duration responses to precipitation and irrigation events is evident from a time series graph of water level (Figure 5).

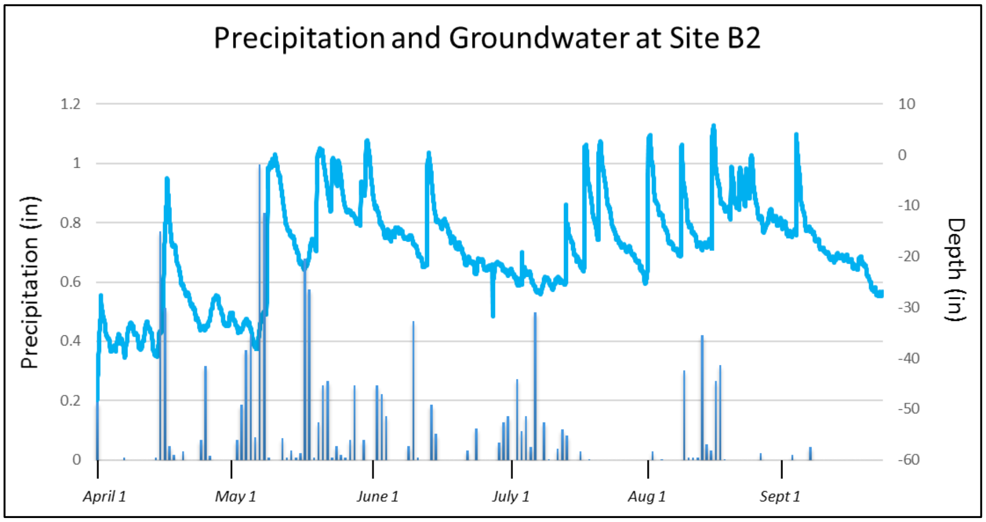



Figure 5: Groundwater level and precipitation at site B2 at 11m into the wetland from the field edge. Precipitation is the dark blue bars with the axis in inches on the left. Groundwater level is the light blue line, with axis in inches on the right. The ground surface is at 0 inches.

Water table was within 2 feet of the surface for 75% of the growing season (April-late September) at 14 of 17 of wells. At the field edge, water tables were within 1 foot of the surface for at least 25% of the growing season. Changes in water level could be rapid following precipitation, such as a 30” rise in two days in early May during a period of substantial precipitation (3 inches in 7 days) at site B1. At the same site irrigation events were observed to raise the water table over 20” in a single day, inundating the edge of field in several inches of water.

Groundwater Chemistry: Nitrate levels in the shallow groundwater spiked during the month of July, but at B1, F and E concentrations were still below the EPA drinking water standard of 10 ppm. One well at site B2 was recorded to had nitrate levels above 20 ppm in July. Background levels for the south sites S1 and S2 were above 20 ppm in June. This was unexpected for S1 as it was fallowed during 2015. S1 and S2 maintained levels above 10 ppm for the entire growing season, peaking at 40.15 in August at S2. Nitrate levels at sites E and F remained below 2 ppm during the 2015 growing season.

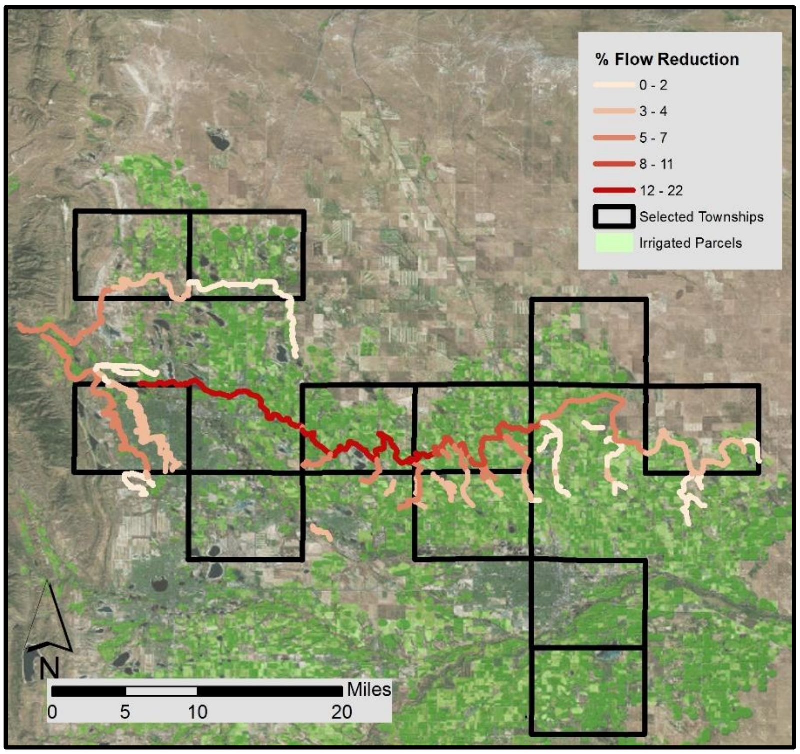
In Situ Denitrification Experiment: A pilot study in 2014 showed that an 8-hour incubation period was insufficient to identify the peak denitrification potential of a soil. The soils in this study were very saturated, with high bulk density which likely slowed the infiltration of acetylene. Thus the incubations were extended to 12-15 hours after the with improved success.

The experiment was conducted at 1 site on July 15$^{th}$ and 3 sites on Aug 13$^{th}$. I sampled site B2 in July with three wells, at 1, 11 and 21 meters into the wetland. Only the wells nearest to the crop field produced satisfactory results with a combination of standing water and incomplete air-tight seals on the chambers corrupting the results of the other two. Specifically, water levels of an adjacent reservoir rose over the incubation period, inundating the chambers. The samples collected at the field/wetland edge produced the highest denitrification rates observed in the study with a peak concentration of $N_2O$ in the chamber of 438.63 ppm. In August B2, B1 and F were sampled with much lower denitrification rates. At 1 meter into the wetland the values ranged from 16.08 to 69.88 ppm and at 11 meters they ranged from 0 to 12.13 ppm.

### *Scenario Results*

Flow reductions of 2-22% were predicted for the ditches in the study area, with mainstem reaches with the largest reductions due to the distributary orientation of the network (Figure 6). Reductions of greater than 10% were predicted for 62.8 kilometers of irrigation ditch. Moderate reductions of 5-10% were predicted for 94.3 km and 2-5% reductions for 171.5 km of irrigation ditch.

Figure 6: Results from flow reduction model on irrigation ditch network.

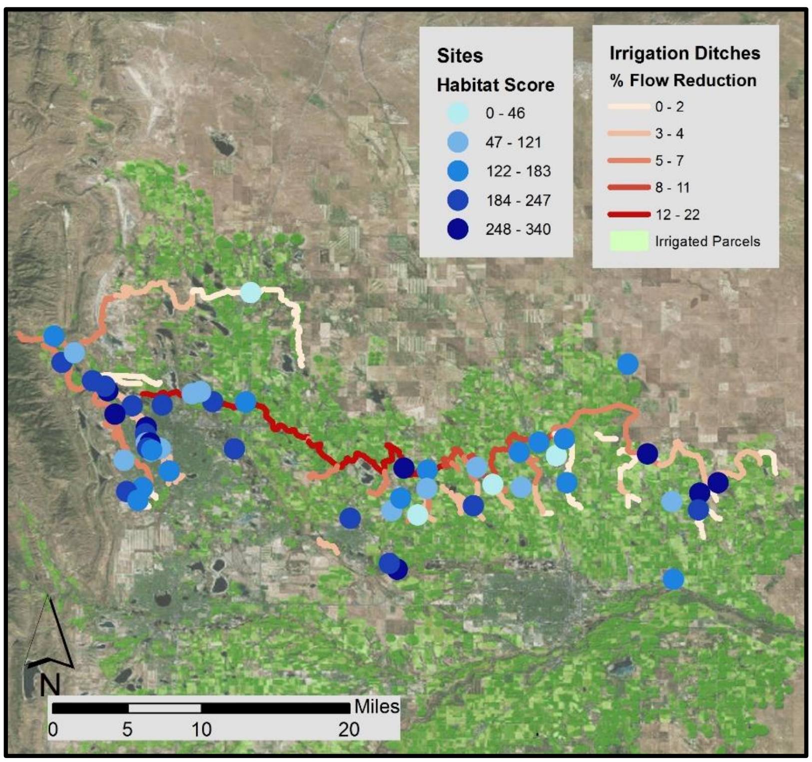



Habitat quality scores ranged from 340 to 0. The average scores are shown for groups of sites using all three spatial scales in Table 4. Overall, ditches had an average of 169 and 181 for streams which was not statistically different using a t-test comparison of means ($p > 0.05$). Wetland cover of streams was higher but the percent native cover was extremely low, (<1%) for two smaller streams. Ditches scored high for the WET parameter when *Phalaris arundinacea* or *Carex emoryi* were dominant as these could be more than 90% of the cover. The nearly ubiquitous presence and often high cover of *Bromus inermis* kept the NATIVE parameter nearly equal between ditch and stream sites at approximately 40% native cover. Some moderate to higher quality sites fell on ditches with the highest expected flow reductions (Figure 7). The mean habitat score for sites along the ditch reaches with the highest predicted reductions in flow was 162.5. The ditches predicted to have the smallest reduction in flows had sites with a mean habitat score of 174.3.

Table 4: Average habitat score for each group with number of sites in ().

| | East Ditches | West Ditches | East Streams | West Streams |
|---|---|---|---|---|
| *Concrete* | 20 (4) | 112 (2) | n/a | n/a |
| *Herbaceous* | 174 (14) | 141 (13) | 119 (2) | n/a |
| *Shrub* | 102 (1) | 222 (2) | n/a | n/a |
| *Light Canopy* | 234 (2) | 246 (4) | 222 (2) | 179 (2) |
| *Heavy Canopy* | 196 (1) | 259 (4) | n/a | 231 (1) |

Figure 7: Locations and habitat scores of field sites including irrigation ditches and streams.




Single variable correlations between habitat score and three physical characteristics of sites were different between regions. The habitat score of East ditches was positively correlated (Pearson r = 0.38) to DIST, WIDTH (r = 0.32), and LAND (r = 0.18). I found the opposite for West ditches for DIST (r = -0.26) and WIDTH (r = -0.31) and LAND was not well correlated in the West.

## Discussion

*Irrigation Ditch Network Discussion*

Ditches and streams have distinct channel and riparian characteristics created by hydrologic and sedimentological processes acting on natural drainage ways and constructed conveyance ditches. Humans affect channel and riparian structure and biotic communities through flow control, vegetation maintenance, and physical alterations to channel beds, banks and floodplain surfaces. However, our observations show similarities between riparian vegetation and aquatic macroinvertebrate communities of streams and ditches. Furthermore, when plant taxa are grouped by ecological function, for example fruit bearing shrubs or non-native grasses, the small differences disappear. The same was true for aquatic macro-invertebrates when trait-based ecological groupings were used instead of taxa.

It is critical to understand the amount, ecological character and location of additional riparian area bordering ditches and the aquatic habitat.

Hydrology: It is important to recognize that the streams are disturbed riparian and aquatic ecosystems. Smaller streams are influenced by storm-water runoff from urban, suburban and agricultural land and the Cache la Poudre River is managed along its length with augmented flows from the Colorado River with several large diversions occurring within or just above the study area. Daily flow variation was higher in streams than in most of the ditches. With the ability to open and close flow gates, we assumed a significant amount of flow variation, related to calls for irrigation water.

The difference in the timing of peak flow between ditches and streams was calculated for small ditches peaking an average of 32 days later than small streams. One ditch was not included in this calculation as it consistently peaked 29 days earlier. Large ditches had peak flows more consistently one month after the river. Ditches and streams had similar daily coefficient of variation during the April to October period (ditches: 1.22, streams: 1.41). The strongly seasonal flow in ditches differs from the more perennial streams (data not shown).

Intermittent and ephemeral streams in the area are severely altered though flow is not gauged. This undoubtedly has strong effects on the aquatic macroinvertebrate communities, with a potentially muted effect on vegetation. Irrigation ditches are managed to be intermittent with flow predominantly during the growing season. Ditches had more days of zero flow periods during the April to September period (29.5) than streams (5.3). One small ditch had a 16-year average of 58 days while the perennial Cache la Poudre River averaged 0 no flow days.

Flow is likely reduced along ditches through extractions for crop production, evaporative losses, transpiration by riparian plants, and seepage through the bed and banks. Tributaries contribute flow, municipal and irrigation demands extract water, and return flows augment flow of the Cache la Poudre River along its length throughout the growing season. The reuse of water in a downstream direction contributes to this area serving the needs of nearly 4 million acre feet of demand with only 2 million af of native and augmented supplies (CWCB 2015).

Vegetation: Riparian vegetation composition at stream and ditch sites were compared using species and ecological guilds with the approaches yielding similar results. We expected ditch sites to contain more introduced and annual species which would increase plant diversity, however this was not observed. Diversity does not equate to ecosystem processes derived from plants such as cover and nesting sites and food resources.

A regional difference in woody canopy cover of ditches was significant with 5% of total ditch length in the east under a woody canopy (Light and Heavy Canopy classes) and over 55% in the West. Ditches in the East were dominated by herbaceous riparian vegetation that appeared to be heavily managed, with evidence of mowing, scraping, burning and chemical treatments observed in the field. The addition of woody species and their shading and micro-climatic effects on the understory species composition likely contributed to the vegetation composition difference between regions.

The ubiquitous effect of human land use in the study area has led to the colonization of several aggressive, introduced species, particularly *Phalaris canariensis* and *Bromus inermis* which were found at 76 and 87% of sites. The presence of these species and their high cover values could have contributed to the similarity between east and west streams, as well and east ditches and streams.

The physical structure of ditches could contribute to this. Stream floodplains are low in elevation with the potential for flooding during moderate flow events, whereas the top surface of ditches is designed to never be inundated. This removes at least three disturbance mechanisms (erosion, aggradation and inundation) that could act as an environmental filter on the species that can survive, which could affect periodic inundation. Micro-topographic features on floodplains create soil moisture conditions that can support a variety of wetland and riparian species with varying tolerance of saturated conditions. The similarity of ditches and streams in the east could be related to the disconnection of streams to their floodplains, a general narrowing of the historic floodplain and a shift towards upland vegetation. This process can be natural but is also a common symptom of a degraded stream channel and/or altered flow regime.

Very little quantitative information on vegetation management (mechanical and chemical) could be found. Active removal of woody vegetation along ditches to improve conveyance and maintain access is common practice yet not well documented. Fire is used in late spring to clear brush, litter and debris from the ditch bottom and sides, improving conveyance. Species whose life histories have critical growth or reproductive stages during this period or are intolerant of fire would be exterminated. Vegetation management strategies are limited in residential areas where fire and strong chemical treatments pose a potential threat to humans.

Macroinvertebrates: Aquatic macro-invertebrate diversity and populations are influenced by the physical setting, food type and availability, and hydrologic patterns (Resh et al 1994). These attributes have been created and controlled or are indirectly influenced by humans in irrigation ditches. The physical habitat of the man-made irrigation ditches in our study varied along the network. Fast flowing, cobble-bed ditches were only observed in the West, near the head gates. Bed substrate changed from cobbles to silt at the more distal ends of the ditches, where flow had slowed and only the smallest particles were kept in suspension. Flow was variable between years and during the May-Aug sampling period. The flow patterns of ditches created numerous high and low flow stressors and winter dry periods, creating different environmental filters for aquatic macro-invertebrate communities at each site.

As bed substrate shifted from coarse cobbles to fine grained sand and silt, the EPT taxa indicative of high quality water were not present. This occurred around 13 km from the point of diversion from the river in ditches, beyond where only more tolerant *Baetis*, *Trichorythodes*, and *Siphlonurus* mayflies were found. This could also have related to water temperate which would increase about $20^0$ C over 10 km of ditch in June and up to $110^0$ C in August. Species richness of individual field sampled range from 28 to 0 but when accumulated for the entire study, site-level richness ranged from 53 to 8, highlighting seasonality and inter-annual variability of many taxa. The increase in individuals in distant ditch sites were attributed to abundant Diptera, specifically Chironomidae taxa.

The bed substrate at the distant ends of the irrigation ditch network is composed of mostly fine grain channel beds with warm water, characteristic of higher order rivers following the river continuum concept (Vannote et al. 1980). This habitat occurs in irrigation ditches in increasingly smaller peripheral channels, generally not the main channel. The distributary flow pattern of the irrigation network creates the potential for ecological sinks. Eggs, larvae and nymphs dispersed aerially and through the water column might not reach reproductive maturity due to hydrologic or water chemistry stressors or lack of appropriate substrate or food resources.

The similarity of aquatic macro-invertebrate communities of ditches and streams in our study area could be related to two forms of variability: habitat and hydrology. The hydrology of ditches varied dramatically potentially including the required flow characteristics of many of the taxa occupying streams. Small and large streams have diverse physical habitat also creating a high species richness within the group. For example, of the 74 taxa observed in streams in the west region only 13 were observed in both small and large channels. However, when taxa were grouped into functional guilds there was no difference between the communities. This suggests that while individual taxa change between streams and ditches, the presence and relative abundances of functional groups remains the same. This was not expected considering within growing season dry periods and strongly seasonal flow pattern of ditches.

### *Tail-water Wetland N-functioning Discussion*

Plant Uptake: The highest levels of plant uptake were by *Typha*, at the field edge in soils that were saturated within 12” of the surface for ~1/3 of the growing season (Apr-Sept). The above ground tissue of *Typha* had the highest percentage of nitrogen at 2.2 with *Schenoplectus* at 1.6 and the mixed species biomass slightly higher at 2.0. Thus above ground biomass is a strong indicator of nitrogen uptake.

Nitrate taken into plant tissues, however, does not remove it from the field-wetland system. Management of the wetland vegetation including mechanical harvest or burning could remove the nitrate from the system. Wetlands created and maintained by normal farming practices, including irrigation, are not governed by the EPA or US Army Corps of Engineers wetland permits, thus allowing for vegetation management to be free of environmental permitting.

<u>Microbial Denitrification</u>: Hydrologic, soil and microbial characteristics of the wetland soils suggested that denitrification could occur in the top 12 and 24" of soil. Organic matter content was ~7% by dry weight for most parts of the wetlands, except those which were most consistently inundated. Groundwater levels created saturated conditions within 2 feet of the surface in 82% of instrumented wells. This is the most active zone for microbial denitrification. Microbial biomass increased further into the wetland and with the time of saturation of the top 12" of soil for all but one site.

Microbial biomass was moderately correlated to number of days the sampled soil depth was saturated (Pearson's r = 0.23 for 0-12" and r = 0.34 for 12-24") with a more positive correlation to organic matter content in the same soil layer (r = 0.74 for 0-12" and r = 0.41 for 12-24").

Conditions were challenging for the in-situ experiment and results were mixed but showed a slightly higher denitrification rate nearer to the fields where water tables were lower, but still within 25" of the surface. This could be explained by the ability of the acetylene to penetrate further into the more aerobic soil layers and interact with more microorganisms.

### *Scenario Discussion*

Flow reductions were found to be highest in mainstem irrigation ditches and lower for smaller lateral ditches. Our analysis did not allow for parcel by parcel exploration of water rights transferability. A small lateral could be dried completely and in perpetuity, removing the hydrologic condition of flowing water that maintained riparian vegetation. Thus I felt the lower flow reductions for peripheral ditches underestimate the potential for individual reaches, but might accurately represent the average risk for a larger area.

The mean riparian habitat scores for ditch reaches with a low and high flow reduction risks were similar, 174 and 162.5, respectively. This could be attributed to active vegetation management along the mainstem (high risk) ditches (Figure 8a) and infrequent and shorter duration flows of peripheral (low risk) ditches resulting in similar impacts (Figure 8b). Mowing, spraying and vehicle access were observed along both of these types of ditches.


Figure 8: a) example of a mainstem ditch with significant vegetation management to maintain access road, b) a small lateral ditch

Due to the limited flow records along the ditches, and specifically near the field sites, it is not possible to calculate the reductions in the individual habitat parameters nor the overall score. However, a reduction in habitat scores is expected. Firstly, if flow is reduced the diversity and cover of wetland species could be reduced. A reduction in the physical stressors of the wetland environment including anoxic soils, erosion and sedimentation disturbance created by flowing water could allow for colonization by species less tolerant of flooded conditions. These could be native or non-native which could impact the habitat score in either direction.

The limited effect of the LAND parameter on habitat scores was not expected. This could be related to the subjectively defined scalar used to numerically categorize adjacent landuse. The timing of individual field sampling could also have impacted these results if observations were made immediately after a vegetation treatment, or just prior to one.

## *CONCLUSION*

Human impacts are widespread on landscapes dominated by agriculture and residential landuse. Some natural processes are impaired and ecosystems degraded while others could be created or enhanced. Irrigated agriculture redistributes water from streams and rivers into ditches and canals which provide water to crop fields and animal production facilities. Aquatic and riparian ecosystems are negatively impacted by water extraction by altering natural disturbance processes related to flooding and the spatial extent and interconnectedness of habitat patches. Aquatic and riparian ecosystems develop in and along irrigation ditches and could support some hydrologic and biotic processes similar to natural streams. Measurements of riparian vegetation composition and structure showed similarities between ditch and streams in the East region but differences in the West. Analysis of the aquatic macro-invertebrate communities showed similarity in both regions.

Irrigated agricultural has indirect effects on the landscape as well. Seepage through irrigation ditches and inefficient application of water at the field have created seepage wetlands along ditch and tail-water wetlands at the edge of fields. Many of these are well positioned to intercept surface and shallow groundwater from crop fields. Water coming off agricultural fields often contains chemical components of fertilizers and pesticides applied to enhance crop productivity. Nitrate is a common component and/or derivative of fertilizers, and can become a pollutant at higher concentrations. Nitrate levels in the groundwater of the study area have been recorded above the healthy EPA drinking water standard. This creates a risk to humans consuming water from private wells where the nitrate is not removed. Two natural wetland processes could reduce the contamination from agricultural runoff. First, the biogeochemical process of denitrification that occurs in anaerobic soil of wetlands could help mitigate groundwater with high nitrate levels when physical and biological conditions are favorable. I found suitable conditions for microbial denitrification at the edge of crop fields including high water table, organic matter in the soil, microbial activity, and groundwater with elevated levels of nitrate.

The second process is uptake of nitrogen by wetland plants as they grow and increase aboveground biomass. I found significant nitrogen uptake in the *Typha* dominated wetlands, with lower amounts in *Schenoplectus*, *Carex* and *Phalaris* wetland communities related to lower biomass. However, without a management strategy to remove the aboveground biomass, there would not be a net export of nitrate from the contributing area. A more detailed understanding of groundwater movement below and near irrigated crop fields would be key to advance this work. A comprehensive field scale nitrogen, specifically nitrate, budget would be necessary to fully understand the role adjacent wetlands play in the transformation and uptake of excess nitrate.

The riparian areas bordering irrigation ditches are largely not considered jurisdictional wetlands under the Waters of the US definition. However, they are utilized by plants and animals as a riparian corridor, similar to a stream or river. The composition and type of the habitat varies, as it does along a stream in a human altered landscape. Regional development could change water use from agricultural to municipal customers, affecting how water is distributed across the landscape. Irrigation ditches occupy a similar footprint (in terms of length of channel) as native streams in areas dominated by irrigated agriculture. These changes will affect the amount and timing of flows in irrigation ditches which could in-turn affect the types of riparian vegetation growing along the banks. These new rivers of the West and their riparian and aquatic ecosystems should be considered during regional water planning to meet the growing demand in the future.

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